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BIOGEOCHEMISTRY AND WATER BALANCE OF THE OTTAWA RIVER BASIN

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**A thesis submitted to the School of Graduate Studies and Research in partial
fulfillment of the requirements for the Ph.D. Degree: Science**

Ottawa-Carleton Geoscience Centre

University of Ottawa

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ABSTRACT

A physicochemical database is constructed by linking chemical and stable isotope analyses of the Ottawa River and its tributaries to properties of their catchment basins by overlaying maps of the properties and maps of the catchments utilizing a Geographic Information System (SPANS). Data include bedrock geology, forest type and extent, soil properties such as the organic carbon content of soils, land use, elevation, discharge, precipitation, and temperature.

Deuterium (δD) and oxygen ($\delta^{18}O$) isotopes for the Ottawa River and its tributaries in the spring range from -71 to -92‰ and -9.4 to -12.7‰ VSMOW, respectively. In the fall these values are -51 to -89‰ and -5.1 to -11.7‰ and the discharge weighted average at the mouth of the river, based on monthly samples, is -82 and -10.9‰. From these data, the average isotopic composition of precipitation that falls in the Ottawa River basin is calculated to be -103.8 and -14.5‰ for δD and $\delta^{18}O$, respectively. The slope of the linear regression of these two isotopic parameters is ~ 6.0 . This is considerably less than the slope of the local meteoric water line (7.7). This discrepancy is a consequence of evaporative loss from the surface of the river and its connected water bodies, such as tributaries and reservoirs. This evaporative loss is calculated to be about 8% of the water volume discharged by the Ottawa River.

Based on forty years of daily meteorological and discharge data and utilizing GIS, annual evapotranspiration for the Ottawa River basin is calculated to be 51%. Due to climatic and soil conditions, the upland silicate basins and lowland carbonate basins average 40 and 65% evapotranspiration, respectively. Combined evaporation and evapotranspiration calculations apportion 43% of the water losses in the Ottawa River basin to transpiration plus interception.

Peaks in discharge occur in the spring due to snow melt, and in the late fall due to the cessation of transpiration by frost and are directly out of phase with precipitation inputs which are greatest during the summer. This implies that riverine baseflow is maintained exclusively by groundwater recharge during the non-growing season. Time series and standard statistical analysis show that the upland tributaries flood more slowly and 20-30 days after the lowland tributaries, the latter characterized by short-lived high discharge pulses in the spring and late fall and by very low discharge in the summer and winter due to both physiographic and climatic conditions. Mixing of these shifting fluxes explains the proportional relationship between discharge and concentration observed at the mouth of the Ottawa River. Alterations to the natural hydrological cycle by flow augmentation practices from hydroelectric reservoirs can be pronounced close to the reservoirs in the uplands but they are assimilated downstream by inputs from unregulated tributaries.

The hydrologic cycle interacts with chemical controls (mainly geology) to produce a relatively consistent annual biogeochemical cycle of dominantly natural origin but containing significant human inputs. Generally, both the susceptibility of minerals to weathering and soil respiration rates increase downstream such that low-elevation-low-latitude tributaries, draining easily weathered carbonate terrains with thick productive high- pCO_2 soils, and containing areas with relatively high population density and intense agricultural land use, are characterized by: (1) high concentrations of total dissolved solids (TDS), DIC, Ca^{2+} , Mg^{2+} , Sr^{2+} , have $\delta^{13}C_{DIC}$ of approximately -8‰, and low $^{87}Sr/^{86}Sr$ ratios, representing a geogenic signal; and (2) high

concentrations of Na^+ , Cl^- , and K^+ , representing a mixed anthropogenic and geogenic signal. Conversely, the sparsely populated, high-elevation-high-latitude, chemically resistant, silicate shield catchments are characterized by low TDS, DIC, SO_4^{2-} , Ca^{2+} , Mg^{2+} , NO_3^- , Sr^{2+} , higher Si and Fe_{total} , have $\delta^{13}\text{C}_{\text{DIC}}$ of roughly -16‰ and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and their anthropogenic signal is subdued to non-existent. The chemistry of the Ottawa River itself falls between these two end-members.

Isotopic composition of dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$) for the lowland carbonate and upland silicate tributaries is about -8 and -16‰, respectively. This suggests that (1) the source of DIC to the Ottawa River is soil respiration and carbonate weathering, (2) exchange with the atmosphere is unidirectional or volumetrically unimportant, and (3) in-river respiration and photosynthesis are not significant influences on the river carbon budget. The flux of carbon from the Ottawa River as DIC is calculated to be $4.3 \times 10^{10} \text{ molC/a}$. Utilizing carbon isotopes, 75% of $\text{Ca}^{2+} + \text{Mg}^{2+}$ flux is calculated to originate from carbonate weathering and 61% of the DIC is calculated to originate from organic respiration. The latter represents some 6% of respired carbon in the basin, assuming an average respiration rate of $5 \text{ mmolC/m}^2/\text{hr}$. Based on a diffusion model, CO_2 evasion to the atmosphere from the Ottawa River and its tributaries is estimated to be $1.3 \times 10^{10} \text{ molC/a}$ or 30% of the DIC flux.

Mass balances based on concentrations, discharge, and isotopic constraints, yield the fluxes of sulfate and strontium from the Ottawa River to be 5.8×10^9 and $3.4 \times 10^7 \text{ mol/a}$, respectively. Most of the sulfur originates from atmospheric inputs with less than 10% coming from the dissolution of evaporite minerals, from pore water leaching the Paleozoic and Quaternary lowland sediments, and possibly from direct industrial sulfur contributions. Strontium is purely of geogenic origin with its concentration and isotopes reflecting either old silicate or young carbonate terrains or a mix of these two end-members.

RESUMÉ

Biogéochimie et bilan hydrologique du bassin de la rivière des Outaouais

Une banque de données physico-chimiques fut créée en liant les analyses chimiques et isotopes stables de la rivière des Outaouais et de ses tributaires avec les propriétés de leurs bassins en superposant les cartes des ces propriétés aux cartes des bassins à l'aide de SPANS, un système d'informations géographiques (SIG). Les données comprennent les unités géologiques, le type et l'étendue des forêts, les propriétés des sols (par exemple leur contenu en carbone organique), l'utilisation du territoire, la topographie, le débit, les précipitations, et la température.

Au printemps, la rivière des Outaouais et ses tributaires ont composition isotopique variant de -71 à -92‰ VSMOW pour le deuterium (δD) et -9.4 à -12.7‰ VSMOW pour l'oxygène ($\delta^{18}O$). À l'automne, ces valeurs respectives sont de -51 à -89‰ et -5.1 à -11.7‰, et leurs moyennes à l'embouchure de la rivière, pondérées par le débit et basées sur un échantillonnage mensuel sont de -82 et -10.9‰. La composition isotopique des précipitations qui tombent sur le bassin de la rivière des Outaouais fut estimée à partir de ces données à -103.8 et -14.5‰ pour δD et $\delta^{18}O$, respectivement. La régression linéaire de ces deux paramètres isotopiques donne une pente d'environ 6.0. Ceci constitue une valeur considérablement plus faible que la pente de la droite météorique locale. Cette inconsistance résulte de la perte par évaporation à la surface de la rivière et des eaux s'y rattachant, tels les tributaires et réservoirs. Cette perte par évaporation représente environ 8% de l'eau déversé par la rivière de Outaouais.

L'évapotranspiration annuelle dans le bassin de la rivière des Outaouais fut estimée à l'aide d'un SIG à 51%, à partir de données météorologiques quotidiennes et des débits au cours des quarante dernières années. À cause du climat et des conditions du sol, l'évapotranspiration moyenne est de 40% dans les hautes terres formées de silicates, et de 65% dans les basses terres carbonatées. En combinant évaporation et évapotranspiration, 43% des pertes en eau dans le bassin de la rivière des Outaouais sont attribuables à la transpiration et à l'interception.

Le débit est à son plus haut niveau au printemps lors de la fonte des neiges, ainsi qu'à l'automne alors que le gel inhibe la transpiration, ces sommets étant hors-phase avec l'apport des précipitations, les quelles sont à leur plus haut niveau durant l'été mais sont équilibrées par les pertes par transpiration. Ceci implique que l'écoulement riverain est maintenu exclusivement par l'apport des eaux souterraines en dehors de la période de pousse. L'étude des séries temporelles et les méthodes statistiques standards démontrent que les tributaires des hautes terres coulent plus lentement de 20 à 30 jours après les tributaires situés dans les basses terres, ces derniers étant caractérisés au printemps et à l'automne par des périodes de courte durée où le débit est plus élevé, et par un débit très faible pendant l'été et l'hiver à cause des conditions physiographiques et climatiques. La combinaison de ces débits variables explique le rapport entre le débit et la concentration observés à l'embouchure de la rivière des Outaouais. Les changements au cycle hydrologique naturel, causés par l'augmentation de débit reliée à l'opération de réservoirs hydroélectriques, peuvent être préenancés près de ceux-ci dans les hautes terres, mais sont assimilés en aval par les tributaires non contrôlés.

L'interaction entre le cycle hydrologique et certains facteurs chimiques (en particulier la géologie) produit un cycle biogéochimique annuel qui soit relativement constant, ayant une origine en grande partie naturelle, mais qui compte des apports humains importants. De façon générale, l'érosion des minéraux et les taux de respiration des sols tendent à augmenter en aval, de façon à ce que les tributaires de basses altitudes et latitudes, puisqu'ils drainent des régions carbonatées facilement érodées recouvertes de sols épais et productifs ayant un pCO_2 élevé dotées d'une densité élevée de population et d'une utilisation agricole intense, sont caractérisés par: (1) des concentrations élevées en solides totaux dissous (STD), CID, Ca^{2+} , Mg^{2+} , Sr^{2+} , avec un $\delta^{13}C_{CID}$ d'environ -8‰ et des rapports $^{87}Sr/^{86}Sr$ faibles, représentant un signal géogène; et (2) des concentrations élevées en Na^+ , Cl^- , and K^+ , représentant un signal anthropogène et géogène mixte. Réciproquement, en hautes altitudes et latitudes, les bassins hydrographiques silicatés, faiblement peuplés et ayant une barrière résistive chimique, sont caractérisés par de faibles valeurs en STD, CID, SO_4^{2-} , Ca^{2+} , Mg^{2+} , NO_3^- , Sr^{2+} , de plus hauts Si et Fe_{total} , ont un $\delta^{13}C_{DIC}$ d'environ -16‰ et un rapport $^{87}Sr/^{86}Sr$ élevé, et leur signal anthropogène est de faible à non-existant. La composition chimique de la rivière des Outaouais se retrouve entre ces deux extrêmes.

Des carbonates des basses terres et des silicates des hautes terres ont une composition isotopique en carbone inorganique dissout ($\delta^{13}C_{CID}$) d'environ -8 et -16‰, respectivement. Cela suggère que (1) le CID dans la rivière des Outaouais provient de la respiration du sol et de l'érosion des carbonates, (2) l'échange avec l'atmosphère est unidirectionnel ou bien constitue un volume de peu d'importance, et (3) la respiration et la photosynthèse en rivière n'a pas d'influence significative sur le bilan en carbone de la rivière. Le débit en carbone provenant de la rivière des Outaouais se calcule à 4.3×10^{10} molC/a CID. Les isotopes de Carbone révèlent que 75% du $Ca^{2+} + Mg^{2+}$ proviennent de l'érosion des carbonates et que 61% des CID proviennent de la respiration organique. Ce dernier facteur représente quelque 6% du carbone qui est respiré dans le bassin, en supposant un taux de respiration moyen de $5 \text{ mmolC/m}^2/\text{hr}$. À partir d'un modèle de diffusion, on estime que la rivière des Outaouais et ses tributaires laissent échapper dans l'atmosphère 1.3×10^{10} molC/a ou 30% du bilan de CID.

Le sulfate et le strontium ont un débit dans la rivière des Outaouais de 5.8×10^9 et 3.4×10^7 mol/a, respectivement, tel que révélé par les bilans de masse à partir des concentrations, débits et des contraintes isotopiques. La majorité du soufre provient d'un apport atmosphérique, dont 10% sont issus de minéraux évaporites, de l'eau contenue dans les pores des sédiments paléozoïques et quaternaires des basses terres, et possiblement d'apports industriels de soufre. Le strontium est d'origine purement géogène, sa concentration et sa composition isotopique résultant de terrains composés de vieux silicates, de jeunes carbonates, ou bien d'un mélange de ces deux types.

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DEDICATION

There are holes in the sky where the rain gets in

The holes are small

That's why the rain is thin

- Spike Milligan

FOR: Fred and Margo and Maycira

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1 INTRODUCTION

1.1 OVERVIEW

Chemical evolution of river water in space (down-stream) and in time is a result of an interaction of geogenic and anthropogenic factors. Polluted rivers acquire higher loads of dissolved salts and an excess of dissolved CO₂ down-stream. It is believed that anthropogenic input of nutrients may stimulate organic productivity, which, in turn, is oxidized to CO₂ that evades into the atmosphere and contributes to the "greenhouse" effect. Yet, similar trends are also evident in relatively unpolluted rivers, such as the Amazon (Stallard, 1980), where the respiration and evasion can be attributed mostly to recharge from floodplains. The Ottawa River is relatively unaltered, evolving from a "pristine" shield stream at its headwaters into a moderately industrialized and polluted river that is buffered by carbonate-rich sedimentary rocks down-stream. The purpose of this research is to study the evolution through space and time of water chemistry in the Ottawa River system.

1.1.1 Carbon Cycle

The impetus for doing this research comes mainly from some unsolved aspects of the global carbon budget. The global carbon budget predicts that about 5.3×10^{15} g of carbon is released annually from burning of fossil fuels (Berner and Berner, 1996). About 2.8×10^{15} g of this carbon accumulate as CO₂ in the atmosphere, resulting in the much discussed greenhouse effect. Rivers, linking the terrestrial system and the ocean, transport yearly about $0.3-0.6 \times 10^{15}$ g of carbon in particulate and dissolved forms (Degens et al., 1987). Studies of dissolved CO₂ in some major rivers, such as the Amazon, Changjiang (Yangtze) or Rhine (Stallard, 1980;

Devol et al., 1987; Richey et al., 1988, 1990; Gao and Kempe, 1987; Kempe, 1982; Buhl et al., 1990), showed that CO₂ concentrations in these rivers are about 10-15 times greater than expected for an equilibrium with the atmosphere (350ppm). Such high values are reached especially in the down-river sections of the rivers. These observations document that the rivers not only transport carbon from land to oceans, but also are actively degassing CO₂ and CH₄ into the atmosphere, with the residence time of CO₂ in the water approximated at roughly 4 days. The evasion rate is not yet quantified, but appears to be at least in the 10¹³ g/a range (Degens et al., 1991; Kempe, 1982). The role of rivers in the global carbon cycle may be substantial, even compared to anthropogenic flux. The major sources of carbon contributing to the total dissolved CO₂ in natural waters are: atmospheric CO₂, CO₂ derived from the decay of organic matter, and dissolution of carbonate. The $\delta^{13}\text{C}$ of CO₂ in fresh water can be used to identify the source(s) of this CO₂ (e.g. Tan, 1989). Isotopic studies confirmed that the CO₂ in the Amazon or the Rhine originates from decomposition of organic matter (Richey et al., 1988; Buhl et al., 1991). Since significant quantities of nutrients (e.g. N, P) that originate from industrial and agricultural discharges as well as from natural sources are transported by rivers (Meybeck, 1982), it is believed that nutrient supply may stimulate organic productivity and the generated organic matter is subsequently oxidized in the water column and in bottom sediments. At this stage, it is not clear what proportion of the above mentioned CO₂ flux results from anthropogenic pollution, and what proportion is the result of natural influx from tributaries and from flood plain drainage. If the flux of CO₂ (and CH₄) evasion from water bodies approximates the above discussed magnitude, the consequences for the global carbon budget and for Global Change scenarios could be considerable. Such a large source would

demand additional sinks; the identified sinks being already insufficient to accommodate some $\frac{1}{2}$ of anthropogenic CO_2 that is "missing" in the atmosphere. In a recent review on the carbon cycle, Toggweiler (1995) illuminates the problems, showing that the widely accepted oceanographic scenario of CO_2 uptake is not a solution to this dilemma and stresses the importance of the natural carbon cycle involving rivers. Quantification of this cycle demands an understanding of the spatial (down-river) and temporal (seasonal and secular) dynamics of carbon in rivers. In order to do so, an understanding of the hydrologic regime of the river and its major tributaries as well as their chemical and isotopic attributes is necessary. The accumulated experimental data from such an undertaking can also be used as a baseline for evaluating local and regional riverine pollution.

1.1.2 Previous Work on the Ottawa River

The flow rates and some basic chemistry of Canadian rivers have been monitored by Environment Canada and related institutions at specific stations for several decades. These records and reports, although fragmentary and frequently internally inconsistent, provide a historical framework for this study. The data for the Ottawa River and its tributaries was made available by Environment Canada and is used and discussed throughout the thesis.

Metal and organic pollutants in the St. Lawrence River have already been studied by Allan (1988), Kaiser et al. (1990) and Lum et al. (1991) and Merrit (1975) studied the variations in trace element concentrations along a stretch of the Ottawa River. Ramamoorthy and Rust (1976) evaluated sorption and desorption characteristics of mercury in some Ottawa River sediments.

1.1.3 Original Contribution

The original contributions of this thesis to the scientific body include:

1. Revised estimates of the basinal area and mean annual discharge of the Ottawa River basin.
2. Estimates of the area covered by different units of geology, forestry, landuse, and soil conditions for the Ottawa River basin and its tributary subbasins.
3. Estimates of average basinal altitude for the Ottawa River basin and its tributaries.
4. A database of chemical and isotopic analyses based on field and laboratory work.
5. A database of chemical analyses extracted and calculated from Environment Canada's Envirodat water quality database.
6. A GIS database containing digital bedrock geology, watershed boundaries, hydroelectrical parameters, population distribution, and elevation.
7. New field and laboratory methodologies for collecting samples, filtering, and pH measurement.
8. A hydrological model of the Ottawa River basin based on meteorological, hydrological and isotopic constraints.
9. A technique for separating basinal evapotranspiration into its component parts, evaporation and transpiration.
10. A biogeochemical model of the Ottawa River basin based on hydrological, chemical and isotopic constants.
11. Estimates of the sources and fluxes of major elements from the Ottawa River basin.

The techniques and models can be applied to other river basins and assist in further understanding and constraining the geochemical exogenic cycle.

1.2 OBJECTIVES

1. Investigation of the dynamics of the Ottawa River: that is its chemical evolution downstream during low and high water stands and its seasonal fluctuations inter-annually. Study of the significance and causes of the observed chemical evolution and the quantification of fluxes.
2. Calculation of the total dissolved CO_2 and quantification of the CO_2 contribution from different sources, such as growing/decomposing organic matter, dissolution of carbonate bedrock and till, and atmospheric inputs. Evaluate the proposition that human impact such as nutrient loading from agriculture or forestry practices, is affecting the atmospheric CO_2 budget and if so quantify the CO_2 flux that is stimulated by anthropogenic loading, as opposed to that originating from riverine plankton or from the flushing of organics from adjacent flood plains.
3. Investigation of the impact of anthropogenic pollution sources (ex. industrial discharge, communal discharge, diffuse agricultural runoff, road salting) on the inorganic chemistry of the river.

1.3 HYDROLOGY

1.3.1 General Characteristics

The Ottawa River is the largest tributary of the St. Lawrence River. The total drainage area of the Ottawa River basin above its outlet into the St. Lawrence from the Lake of the Two Mountains near Montreal is 149,000 km² (64% or 95,400 km² in Quebec, and 36% or 53,600 km² in Ontario), representing approximately 11.2% of the total drainage area of the St. Lawrence River basin (1,315,000 km²). This drainage area is exceeded only by a few Canadian rivers, namely: the Mackenzie (1,805,000 km²) and some of its tributaries (Peace, Liard, and Athabasca), the Nelson (1,070,000 km²) and its tributary, the Saskatchewan (414,000 km²), and by the Fraser (232,000 km²). It is the largest all-Canadian river in the eastern part of the Country (Canada Department of Northern Affairs and Natural Resources, Water Resources Branch, 1962). The mean annual discharge of the Ottawa River is 1933 m³/s (Atmospheric Environment Service, 1994). Figure 1-1 shows the Ottawa River basin in the context of the Great Lakes-St. Lawrence system.

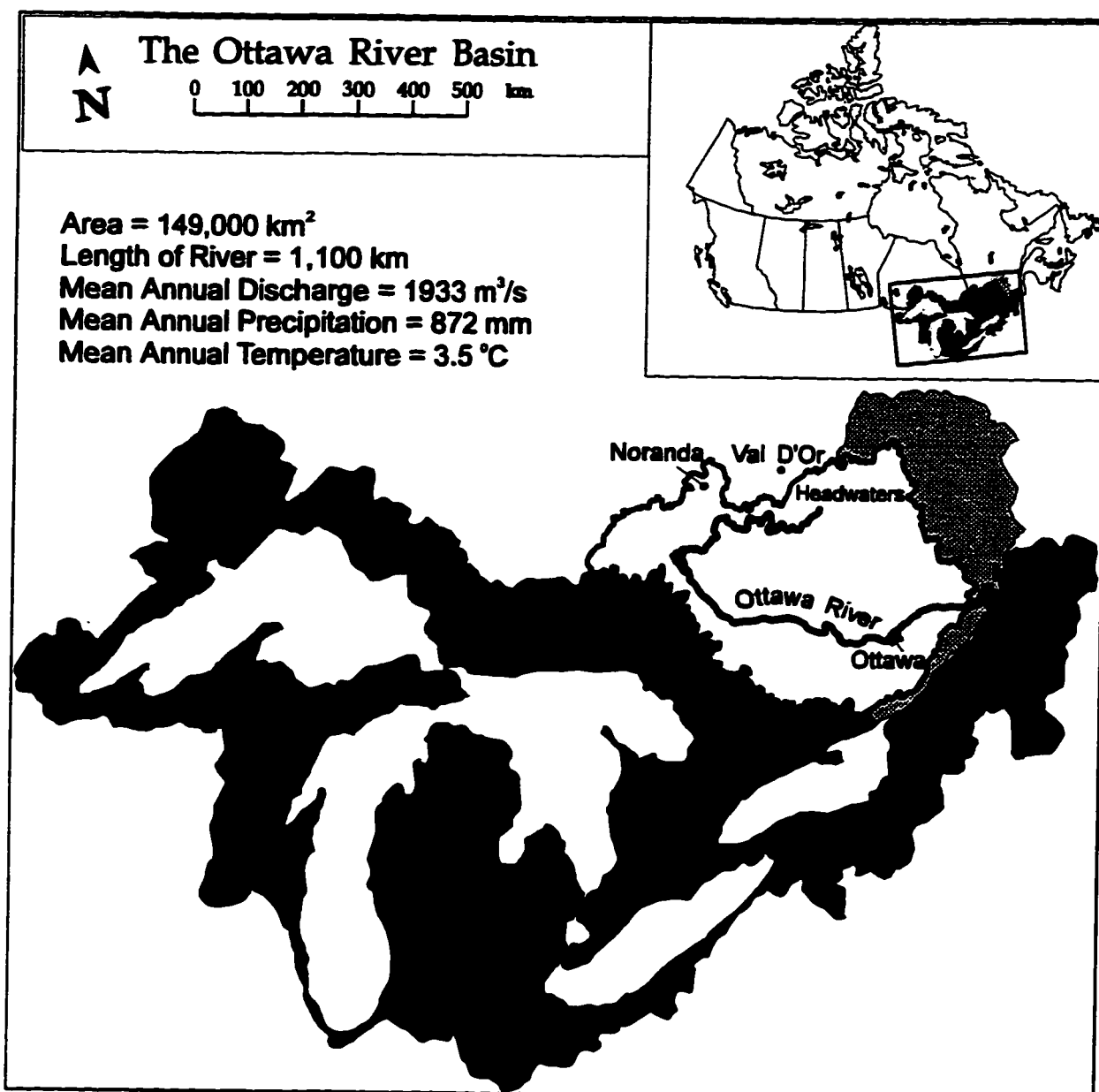


Figure 1-1: The Ottawa River basin.

The Ottawa River basin extends between 73°30' and 81°22' longitude west and 44°34' and 48°42' latitude north. It is bounded on the north by the Mattagami, Abitibi, Harricana and Nottaway river basins which flow to James Bay, and on the east and northeast by the St. Maurice River basin, a tributary of the St. Lawrence. The adjacent areas to the south and southeast are drained by a series of small tributaries of the St. Lawrence River and the areas to the southwest by tributaries of Lake Ontario, the principal one being the Trent River system.

Immediately to the west, tributaries drain into Georgian Bay, the French River basin being the largest.

The Ottawa River springs in Lake Chapitchimagama in the northeastern part of the basin and heads westward towards the head of Lake Temiskaming. It then pursues a southeasterly course to the city of Ottawa and thenceforth travels east to its confluence with the St. Lawrence River at Montreal. The total length of the Ottawa River is 1160 km and its vertical descent is 365 m, producing an average slope of 0.315 m/km. 84 m of this plunge occurs in a short 22.5 km stretch between Lake Quinze-Simard and Lake Temiskaming. The remainder occurs more gradually over the course of the river (Ottawa River Engineering Board, 1965).

Like many rivers which traverse recently glaciated terrain, the Ottawa River consists of a chain of lakes connected by sections of river, rapids and waterfalls. In many ways it can be considered a lacustrine river although not to the extent of the St. Lawrence system which includes the Great Lakes. The upper-basin lakes, such as Lac Dozois, Grand Lac Victoria, Lac Simard, Lac Des Quinze and Lake Temiskaming, are larger than those of the lower basin along the interprovincial border. Between Temiskaming, at the foot of Lake Temiskaming, and the city of Ottawa, the river broadens and contracts into Lac Allumette, Lower Lac Allumette, Lac Coulonge, Lac Rocher Fendu, Lac Des Chats and Lac Deschenes. Below Ottawa, the reservoir behind the Carrillon Dam is the only substantial lake-like expansion before the river joins the St. Lawrence River. Many of the above mentioned lakes are used for water storage to optimize electricity generation. Most of the rapids in the Ottawa River have been harnessed for electricity generation. The Ottawa River basin is one of the most regulated in Canada (Ottawa River Regulation Planning Committee, 1980).

1.3.2 Tributaries

The Ottawa River has 28 significant tributaries, 24 of them below Lake Temiscaming, with an equal number in Quebec and Ontario. Of these 28 tributaries, 21 carry more than 95% of the cumulative tributary flow with the Rivière Gatineau being the largest. More details on relative flows are given in chapter 4, dealing with water balance. The 21 largest tributaries were selected for sampling in this study. Table 1-1 lists the tributaries by province and from the headwaters to the mouth. Those sampled in this study are indicated by asterisk.

Ontario Bank Tributaries	Quebec Bank Tributaries
Blanche River*	Rivière Camachigama*
Montreal River*	Rivière Kenojévis*
Matabitchuan River	Rivière Kipawa*
Jocko River	Rivière Dumoine*
Mattawa River*	Rivière Schyan
Petawawa River*	Rivière Noire*
Indian and Muskrat Rivers	Rivière Coulonge*
Bonnechere River*	Rivière Quyon
Madawaska River*	Rivière Gatineau*
Mississippi River*	Rivière du Lièvre*
Rideau River*	Rivière Blanche
South Nation River*	Rivière du Petite Nation*
Rigaud River*	Rivière Rouge*
Requette River	Rivière du Nord*

Table 1-1: Tributaries of the Ottawa River. Tributaries marked with * were sampled in this study.

1.3.3 Drainage Patterns

The main valley of the Ottawa basin is a reflection of major structural features, primarily faults relating to rifting in the Precambrian and Paleozoic which were re-activated most recently during Late Cretaceous and Early Tertiary times. Tributary drainage patterns in the Canadian Shield portion of the basin are also governed by bedrock structure. Tributaries in the lower basin, draining areas covered with thick glacial drift, glaciomarine and glaciolacustrine deposits, have generally incised into this plain since ice retreat but have managed to reoccupy pre-glacial valleys (Occhietti, 1989). Terracing has also occurred where streams, including the Ottawa River, have been superimposed on Quaternary sediments. On

the plain of each terrace the rivers generally open into lake-like expansions giving these systems a partly lacustrine nature.

1.4 CLIMATE

Climate zonation within the basin is more or less along lines of latitude. Average meteorological conditions - precipitation, evaporation, and temperature - are calculated from meteorological data in chapter 4 but in general the climate is similar to many parts of the Canadian Shield and St. Lawrence lowlands and can be classified as humid continental with mesoscale local effects caused by the Great Lakes and Hudson Bay (Farvolden et al., 1988). An average of 880mm of precipitation fall in the basin annually and 445mm of this leaves in the form of runoff (Ontario Water Resources Commission and the Quebec Water Board, 1971). These estimates are recalculated to be 872 and 427mm from GIS analysis as discussed in chapter 3.

1.5 PHYSIOGRAPHY

The diverse physiography of the Ottawa River basin has been formed and controlled over the past 3 billion years by a wide array of geological processes including volcanism, sedimentation, plutonism, faulting, mountain building, erosion, burial, uplift, weathering and glaciation. The most recently active of these processes have been glaciation, roughly 20,000 years ago, and faulting. Faults along the Ottawa-Bonnechere Graben are presently active (Sage, 1991; Riamundo, 1994). Two major physiographic units exist in the Ottawa River basin, the uplifted broad dome of the Canadian Shield and the surrounding flatter lowlands called the Borderlands in Ontario (Bostock, 1970). Compared to the Borderlands, the

Canadian Shield is topographically higher and composed of more resistant material and therefore being the primary influence on drainage patterns. Generally, in the Ottawa River basin, a multitude of lakes and rivers flow off the Canadian shield onto the Borderlands and ultimately into the St. Lawrence River.

1.5.1 Topography

The margins of the Ottawa River basin are defined by 4 topographic features, the cratonic Frontenac Arch to the west, the Cobalt Plain to the north which rests on the edge of the cratonic Fraserdale Arch, the Beauharnois Anticline to the east which is part of the larger cratonic Laurentian Arch, and the St. Lawrence River valley to the south which runs parallel to the Allegheny-Quebec-Anticosti basins, the foreland basins of the Appalachian orogeny (Thurston, 1991; Sanford, 1993).

The topography of the Ottawa River basin is mainly the result of the denudation of two extinct orogenic belts and subsequent glaciation. The denuded Laurentian mountains (produced during the Appalachian orogeny) predominate in the east and north east of the basin and form the highest topography in the Mount Tremblant area. In the west, the Algonquin dome and the Madawaska highlands (the roots of the older Proterozoic Grenvillian orogeny) form the topographic highs. The Temiskaming Rift Zone in the north-west and the Ottawa-Bonnechere Graben in the southeast and south of the basin form the main lowlands which divide the topographic highs. Faults such as the Eardley Fault which strikes north west from Ottawa, forming one part of the headwall of the Ottawa-Bonnechere Graben, can form steep topographic boundaries.

1.6 GEOLOGY

1.6.1 Precambrian Rocks: the Canadian Shield

Precambrian rocks occupy roughly three quarters of the Ottawa River basin and are divided into three provinces, the Superior Province, the Southern Province, and the Grenville Province.

1.6.1a The Superior Province

The oldest rocks in the basin, of Archean age, are found in the Pontiac Belt of the Superior Province in the north west of the basin just east of Lake Temiskaming. They consist of a number of parallel east-west-trending supracrustal assemblages of volcanic, pyroclastic and sedimentary rocks preserved as elongate synclinal keels between more extensive regions of granitoid rocks (Church and Young, 1972). The grade of metamorphism for the granitoids is generally lower amphibolite facies (Baer et al., 1971). The volcanic and pyroclastic rocks of the Superior Province occurring in the Ottawa basin are a subset of the Archean Greenstone Abitibi Volcanic Belt called the Blake River Group (Allard et al., 1972). These rocks are mainly intermediate to acid (andesite to rhyolite) volcanics, basalts are present but less common. There is a paucity of potassium and an abundance of silica in these rocks. They have been described as "sodic rhyolites" and exhibit very high Na/K ratios (Allard et al., 1972). The metamorphic grade of the volcanics is low (greenschist facies) but alteration is pervasive. The breakdown of plagioclase and ferruginous minerals to sausserite and chlorite is very common. These rocks have been mined productively for base and precious metals since the turn of the century (Allard et al., 1972). Immediately to the south of the main volcanic sequence is a band of sediments consisting of conglomerate, greywacke and schists belonging

to the Pontiac Group. Volcanic rocks were the dominant source of the sedimentary rocks, most of which are mineralogically and texturally immature turbidites (Church and Young, 1972). Grade of metamorphism increases in a southerly direction increasing from greenschist to amphibolite facies (Allard et al., 1972). Archean conglomerates occur in their type locality in the Lake Temiskaming region. They exist as inliers within areas of flat-lying Proterozoic (Huronian) and Paleozoic rocks and were largely derived from volcanic terrain of intermediate to acid composition and also contain plutonic boulders (Church and Young, 1972).

1.6.1b The Southern Province

In the Cobalt Embayment of the Southern Province, late Lower Archean clastics of the Huronian rest unconformably on inliers of Archean volcanics and on iron formation (Baer et al., 1971). In the Cobalt area, the Huronian Group is composed of the Gowganda and Lorrain Formations (Pye et al., 1972). The Gowganda is considered to be of glacial origin and is separated into a lower unit composed of tillites and an upper sequence of fine-grained stratified terrigenous clastic rocks. The upper part of the Lorrain Formation is an extremely mature orthoquartzite (Church and Young, 1972) and the lower part has been described as "mature shelf-type clastic sediments" (Pye et al., 1972). Together these two formations form the Cobalt Group. The sediments are intruded by the sills and dykes of the Nipissing diabase and are broken by normal faults of several ages. The rocks are moderately deformed but not metamorphosed. The deformation results most likely from the Hudsonian and Grenvillian orogenies (Baer et al., 1971). Silver, iron and cobalt are the main elements mined from these rocks but nickel, copper, lead, bismuth, arsenic and antimony were also extracted. The main ores are native silver, complex arsenides, antimonides and sulfides (Pye et al., 1972).

1.6.1c The Grenville Province

The Grenville Province which was first described by Logan (1863) occupies roughly three quarters of the Precambrian terrain in the Ottawa River basin. Hoffman (1989) separates it into three distinct zones, a north-western parautochthonous zone, a central allochthonous polycyclic zone, and a southeastern allochthonous monocyclic zone, all present in the basin.

North-Western Zone

The North-western Zone, which represents roughly 45% of the Grenville rocks in the basin, is composed of rocks directly related to those in the adjacent Archean terrain but bearing a Grenvillian structural and metamorphic (greenschist- to granulite-grade) overprint. In the Ottawa River basin these rocks are represented primarily by the Quebec Gneiss Belt, which is predominant in the headwaters area of the basin in the north-east, and the Ontario Gneiss Belt, which lies in the western and central parts of the basin.

The Ontario Gneiss Belt is considered to be the metamorphic equivalent of the Lower Aphebian, Huronian Supergroup of the Southern Province. These gneisses are dominantly quartzofeldspathic, pink or grey, well layered, and mainly at amphibolite, rarely granulite, grade of metamorphism. The dominant structural grain is northwest and considered to be Hudsonian (Baer et al., 1971). The dark grey gneisses of the Quebec Gneiss Belt are considered to be Archean in age and their dominant structural grain points to a possible Kenoran influence. The presence of granulite metamorphic grade rocks is more common than in the Ontario Gneiss Belt.

Central Zone

The Central Zone contains amphibolite- to granulite-grade gneisses which bear little genetic similarity to the rocks of the northwest. The boundary between the North-west and Central Zones is defined by geophysical anomalies marking the leading edge of high grade allochthons overriding lower grade rocks to the northwest. In the Ottawa River basin, the Central Zone is thin to non-existent and poorly defined where it is present. A thin piece of the southeastern part of the Ontario Gneiss Belt may constitute some of the Central Zone as well as northwestern parts of the Central Granulite terrain. For the most part, the Central Zone is missing.

Southeastern Zone

The Southeastern Zone contains belts of juvenile Grenvillian crust such as the Elzevir terrain and belts of older crust such as the Frontenac terrane probably accreted during the Grenvillian orogeny. This zone is well represented in the Ottawa River basin by the Bancroft, Elzevir, Frontenac, Mont Laurier, and Morin terranes. Excluding the Morin, these terranes form the "Central Metasedimentary Belt" (Wynne-Edwards, 1972). The Bancroft terrane consists of middle to upper amphibolite grade marble and siliciclastic metasediments intruded by granodioritic orthogneiss and bodies of nepheline syenite and carbonatite. It should be noted here that along the Ottawa-Bonnechere Graben, lamprophyre dykes are common and several alkalic-carbonatite complexes are present (Sage, 1991). The Elzevir terrane is characterized by greenschist- and amphibolite-grade metavolcanic rocks and related tonalites and granites, intercalated with and overlain by marble and siliciclastic metasediments similar to those in adjacent terranes. Volcanism was mafic and felsic, tholeiitic and calc-alkaline. The

Frontenac and Mont Laurier terranes are roughly equivalent, they are separated by the Ottawa Embayment Paleozoic sediments. These two terranes lack the metavolcanics and tonalites found in the Elzevir terrane but contain similar pattern of marble and siliciclastic sediments intercalated and overlaying gabbro-granite-syenite plutons (Hoffman, 1989). The Morin terrane, roughly the equivalent of the Adirondac highlands in New York, is mainly composed of large anorthosite-gabbro-charnokite-mangerite complexes intruded into siliciclastic, carbonate, and possibly evaporitic metasediments, felsic metavolcanics, leucocratic to melanocratic para- and orthogneisses (Martignole, 1975). This terrane is metamorphosed to granulite grade. The Morin terrane has been called the Central Granulite Terrane in the area of the Ottawa River basin by Baer et al. (1971). It forms the highest topography in the basin.

The southwestern part of the Grenville Province in the vicinity of the town of Bancroft, in particular the area known as the Ottawa River Remnant, contains the thickest sequences and a high proportion of carbonate metasediments. This same area contains the only thick unequivocal metavolcanic sequences and the only sequence metamorphosed to only greenschist facies in the Grenville Province (Lumbers, 1967, 1982).

More details on the Grenville Province can be found in the comprehensive volume compiled by Moore et al. (1986). Davidson's (1986) section on the southwestern Grenville Province covers much of the area which lies in the Ottawa basin.

1.6.2 Ottawa St. Lawrence Lowland - Ottawa Embayment

The Ottawa-St. Lawrence Lowland is a well-defined basin within the greater physiographic province of the St. Lawrence Lowland. The basin occupies altogether an area of roughly 20,400 km² lying between the Laurentian Highlands of the Canadian Shield to the

north and the Adirondack Mountains to the south. Its western margin is bounded by the Frontenac Arch, an irregular, northwesterly trending belt of Precambrian rocks, which connects the Canadian Shield to the Adirondacks and forms the Thousand Islands where it crosses the St. Lawrence River. The Lowland eastern margin is defined by the less well defined Beauharnois anticline which extends from the Canadian Shield near St. Jerome, Quebec, south to the Adirondacks (Wilson, 1964). The portion of the Ottawa-St. Lawrence Lowland which lies in the Ottawa River basin has an area of roughly 11,000 km².

The preserved record of the Ottawa Embayment and Paleozoic outliers of the St. Lawrence Platform, evolved through a complex series of tectonic and depositional events that began in the late Proterozoic and continued through to the end of the lower Silurian.

Sediments in the Ottawa Basin were deposited on a broad continental shelf and in foreland basins along the eastern margin of North America under passive-margin (divergent) and active-margin (convergent) conditions during the opening and closing of the Iapetus Ocean, the Taconic and Appalachian orogenies. Generally, sedimentation in the Ottawa Embayment, Ottawa valley outliers, and Lake Temiskaming outlier occurred during 5 tectonostratigraphic cycles. The nature of these sediments is briefly outlined below within the framework of the 5 cycles. Faulting had a strong control on both deposition and erosion of sediments in the Ottawa Embayment. Faults reach the surface indicating post-depositional, and possibly recent, movement (Riamundo, 1994).

1.6.2a Cycle 1: Uppermost Proterozoic to Canadian

Cycle 1 occurred during continental separation and the opening of the Iapetus Ocean. Rifting and then passive (divergent) margin conditions prevailed. In the area covered by the

Ottawa River basin, sediments were preserved only in the Ottawa embayment while eroded in all other Paleozoic outliers (Sanford, 1993). The following is a description of the units which compose cycle 1.

1. The basal strata of cycle 1 are redbeds known as the *Covey Hill Formation*. They occur sporadically on and marginal to the Frontenac Arch but are continuous in the subsurface to the east beneath much of the Ottawa Embayment. The rocks are red, pink, and white, crossbedded, orthoquartzitic sandstones, arkosic and conglomeratic at the base. The formation is highly variable in thickness as it was deposited in horsts and grabens created by rifting during continental separation. As such it is believed to be uppermost Proterozoic and lowest Cambrian in age. Covey Hill detritus was derived mainly from the rising Frontenac and Laurentian arches and is thus distinctly continental in origin.

Lower and Middle Cambrian marine strata were not deposited in the Ottawa Embayment as they were in other parts of the St. Lawrence Platform. The marine facies of cycle 1 are represented by Upper Cambrian and Lower Ordovician strata of the Nepean, March, and Oxford Formations in ascending order.

2. The *Nepean Formation* lies unconformably on the Covey Hill beds and locally overlaps them to rest on basement rocks. They are typically white and grey-buff to rusty yellowish orange, orthoquartzitic mature sandstones with quartz pebble conglomerate, arkose, and shaly interbeds common at the base and less so higher up in the sequence. The Nepean Formation was deposited in shallow marine to fluvial conditions and its provenance were the highlands of the Frontenac and Laurentian arches. It is thought to be equivalent to the

Late Cambrian Potsdam Formation in northern New York. The Nepean Formation is roughly 180 m thick.

3. The *March Formation* gradually succeeds the Nepean and in some areas around the margins of the Ottawa Embayment it overlaps onto basement rocks. It is light grey to white orthoquartzitic sandstone interbedded with light to medium grey dolostone. Dolostone increases upwards in the sequence. This formation is 10 m thick at its margins increasing to 60 m in the centre of the embayment.
4. The March Formation gives way to the top of cycle 1 sediments represented by the *Oxford Formation* carbonates. These rocks are light to dark greyish-brown stromatolitic dolostones around the margins of the embayment and give way basinward to dark brownish-grey to black micritic dolostones with interbeds of limestone and shale. The Oxford Formation is roughly 125 m thick.

The March and Oxford sequences contain some intraformational breccias, gypsum lenses, halite casts, and mudcracks pointing to a wide variety of depositional environments, from restricted marine to lagoonal, intertidal, and supratidal (Hofmann, 1972).

1.6.2b Cycle 2: Whiterockerian to lower Edenian

The onset of the Taconic Orogeny and hence the transition from passive (divergent) to active (convergent) margin tectonics marks the beginning of Cycle 2. Sediments deposited during this cycle are preserved in the Ottawa Embayment, the Ottawa valley outliers, and the Temiskaming outlier.

OTTAWA EMBAYMENT

1. The *Chazy Group* or *Rockcliffe Formation* is composed of dark grey and olive green, and locally red shales, siltstones, and greenish-grey sandstones, up to 50 m thick in the western part of the embayment (Wilson, 1964). Towards the eastern part of the embayment the upper parts of the Rockcliffe formation become sandstone intertongued with calcarenites. It is thought that the sources of detritus for the formation were the rejuvenated Frontenac and Laurentian arches (Sanford, 1993).
2. The carbonates of the *Black River* and *Trenton Groups* succeed the Rockcliffe Formation. Once extending far across the craton, they now are confined to small remnants in the Ottawa Embayment. Their maximum combined thickness is 213 m in the central part of the embayment.
3. The *Black River Group* (Clark, 1972) is composed of 3 units:
 - a) Pamela formation: 23 m thick; buff-weathering dolostone with interbeds of shale, limestone, and minor sandstone.
 - b) Lowville Formation: 52 m thick; largely thin bedded, tan to dark brown micritic limestone.
 - c) Leray Formation: 8 m thick; massive and thick-bedded, dark brownish-grey fossiliferous limestone.
4. The *Trenton Group* (Clark, 1972; Sanford, 1993) contains four units:
 - a) Rockland Formation: 13 m thick, thinning to the east; medium to thick-bedded, dark brownish-grey, argillaceous, fine-grained limestones, with dark grey shale partings and interbeds throughout.

- b) **Hull Formation:** 37 m thick, thinning to the east; dark grey argillaceous limestone, with dark grey to black shale interbeds, succeeded by light grey, massive bedded calcarenite and bioclastic limestone.
- c) **Verulam Formation:** 30 m thick, thinning to the west; thin-bedded, nodular-bedded, dark grey, shaly limestone, with numerous interbeds of dark grey to black shale.
- d) **Cobourg Formation:** 55 m thick, thinning to the west; dark brown, microcrystalline limestone.

The seas during Chazyan time did not extend far beyond the Ottawa Embayment but later during Blackriveran and Trentonian times, as the Taconic front advanced and subsidence in the St. Lawrence foredeep accelerated, the sea transgressed further over the shield depositing what are now outliers. Blackriveran deposition was confined to the Ottawa valley outliers with substantial remains in the Lake Temiskaming outlier, the largest one.

LAKE TEMISKAMING OUTLIER (Russell, 1984)

- 1. **Guigues Formation:** 30 m thick; red and grey-green orthoquartzitic and arkosic sandstones.
- 2. **Bucke Formation:** 24 m thick; grey and grey-green, sandy shales, containing medium-grey, argillaceous microcrystalline limestone beds, the latter increasing in numbers upward to grade into the overlying beds.
- 3. **Farr Formation:** 30 m thick; medium to dark brown, nodular, microcrystalline limestone containing dolomitized burrows.

1.6.2c Cycle 3: upper Edenian to Gamachian

The peak of the Taconic Orogeny narrowed the St. Lawrence foredeep further in late Edenian and Richmondian time. After a brief regression in the mid-Edenian the ensuing transgression deposited proximal flysch and distal black and grey shales in the Ottawa Embayment, the Lake Temiskaming outlier, and the Clear Lake (Ottawa valley) outlier. In the early Richmondian, following the emplacement of the youngest allochthons marking the final definition of the Taconic front, redbed deposition ensued and is preserved in the Ottawa Embayment. The red shales of the Queenston formation mark the end of the preserved sequence in the Ottawa Embayment and are overlain only by Quaternary deposits. Almost all of the cycle 3 units are preserved in small pockets along the downthrown sides of tilted fault-blocks (Sanford, 1993).

***OTTAWA EMBAYMENT* (Wilson, 1964; Clark, 1972)**

1. Eastview Formation: 8 m thick; alternating dark brown bituminous limestones and black shales; represents the transition from the subjacent Cobourg limestones to the superjacent Billings shales
2. Billings Formation: 52 m thick; black and dark grey shales.
3. Carlsbad Formation: 185 m thick; dark grey and greenish grey shales with minor limestone interbeds near the top.
4. Russell Formation: 12 m thick; dolomitic limestones and interbedded siltstones.
5. Queenston Formation: 13 m thick; red and grey-green mottled shales.

CLEAR LAKE OUTLIER

1. Eastview-Collingwood Formation: 6 m thick; black shale with bituminous interbeds lying conformably on the Cobourg limestones.

LAKE TEMISKAMING OUTLIER

1. Here the Eastview Formation is missing and the Dawson Point Formation lies unconformably on the Farr Formation: 30 m thick; dark grey shales with a thin basal limestone conglomerate.

1.6.2d Cycle 4: lower to mid-Llandovery

Silurian deposition (cycles 4 and 5), which is preserved in the Lake Temiskaming outlier, is thought to have been widespread in the Ottawa Embayment but was subsequently eroded in post-Devonian times. The sea transgressed the platform and adjacent Canadian Shield in the early Silurian and deposited the Wabi Group disconformably on the Upper Ordovician Dawson Point shales in the Lake Temiskaming outlier. The Wabi Group is divided into units which are similar to those found bordering the Michigan basin in Ontario and thus the same nomenclature is used (Sanford, 1993).

LAKE TEMISKAMING OUTLIER

1. *Wabi Group* (Russell, 1984)

- a) Manitoulin Formation: 16 m thick; grey limestone with interbedded dolostone.
- b) Cabot Head Formation: 10 m thick; red and green shales with nodular gypsum.
- c) Dyer Bay Formation: 7 m thick; grey and blue-grey limestones.
- d) Wingfield Formation: 12 m thick; grey and grey-tan, semi-lithographic dolostones with green and red nodular shale interbeds.

1.6.2e Cycle 5: upper Llandovery to lower Ludlow

Strata approximately equivalent to the Fossil Hill and lower Amabel Formations in southwestern Ontario, called the Thornloe Formation, complete the Paleozoic succession at the Lake Temiskaming outlier. During this time the Canadian Shield was widely inundated and uniform open-platform marine environments prevailed.

LAKE TEMISKAMING OUTLIER

1. Lower Thornloe Formation: 39 m thick; alternating grey-buff to light brown limestones and dolostones with a thin basal limestone conglomerate resting disconformably on the Wabi Group.
2. Upper Thornloe Formation: 21 m thick; light grey and grey-tan massive and reefal dolostones.

1.6.3 Quaternary Deposits

Quaternary deposits are abundant in the Ottawa River basin with most related to the last ice retreat and occupation of the area by post glacial water bodies. The only Quaternary deposits in the basin that predate Late Wisconsinan are fluvial sands (overlain by till) at Pointe Fortune near the mouth of the river. They were probably deposited during a Wisconsinan interstade (Veillette and Nixon, 1984).

The last ice to occupy the area was of Late Wisconsinan age and is thought to have been the ice mass that extended to its terminal moraine in New Jersey. It receded between 12,000 and 10,000 years ago (Farvolden and Cherry, 1988). Ice flow was mainly north-south during glacial maxima and became lobate and topographically controlled during the waning stages (Gadd, 1980).

1.6.3a Shield versus the Lowlands

Generally the Canadian Shield portion of the basin is sediment poor, with discontinuous to absent sediment cover (Kaszycki and Shilts, 1987). The most common glaciogenic sedimentary sequences in the southern Canadian Shield are small complex sediment flow assemblages often located on the lee side of bedrock knobs. Basal till is relatively rare and occurs as either a thin (<1m) discontinuous mantle or as more rare <5m isolated deposits filling or flanking narrow troughs in bedrock. Most glaciogenic sediment found in the Shield is thought to have been deposited during meltout or ice stagnation (Kaszycki, 1987). Kaszycki and Shilts (1987), argue convincingly that there has been little modification of the Precambrian surface of the Canadian Shield by Pleistocene glaciers. They estimate a maximum of 1-2m of erosion during the Late Wisconsinan glaciation.

Conversely, the Ottawa-Embayment lowlands are generally thickly covered by glacial sediments. Klassen (1987) claims that differences in the patterns of landform development can be explained by regional variations in susceptibility of various bedrock terranes to glacial erosion. For instance, large intrusive bodies, such as the anorthosites in the eastern part of the basin or the Ontario and Quebec gneiss belts, are relatively resistant, producing little glacial sediment and, consequently, few constructional landforms. Supracrustal sedimentary sequences, such as the Ottawa Embayment Paleozoic sediments in the southern part of the basin, on the other hand, produce much more debris which is expressed by continuous drift cover and by well-developed constructional landforms on and down-ice from their outcrops.

1.6.3b Till and glaciofluvial sediments

Till deposited during the Late Wisconsinan is the most extensive Quaternary sediment in the area despite the extensive glaciomarine deposits of the Champlain sea (Fulton, 1987).

The till is generally sandy and the texture of the fine portion in areas underlain by Paleozoic rocks has a slightly higher silt than clay content than that in areas underlain by Precambrian rocks (Kettles and Shilts, 1983). Carbonate-rich facies of till coincide closely with local carbonate bedrock geology, with the carbonate content of tills increasing rapidly where the ice moved from an area underlain by Precambrian crystalline rocks to one underlain by carbonate-rich Paleozoic rocks (Kettles, 1988a; b). The distribution of trace elements also is closely tied to local bedrock composition. For example, high arsenic values in till relate well to a number of small mineralized areas in the Precambrian bedrock and high levels of Zn, As, Fe, Pb, Mn, Cd, Mo, Hg, and U are related to belts of metasediments and metavolcanics in the Frontenac Arch (Kettles and Shilts, 1983). High values of Co, Cr, and Ni are related to the occurrence of large basic plutons as well (Kettles, 1990; 1992).

Glaciofluvial sediments are common in the basin. Eskers are common on the Precambrian Shield, particularly on the Frontenac Arch and Madawaska Highlands. Outwash fans and outwash plains are common at the northern limit of the Champlain Sea (next section).

1.6.3c Champlain Sea

Deglaciation of the area was followed by submergence under the Champlain Sea, an arm of the Atlantic Ocean that extended up the St. Lawrence River into the isostatically depressed lower Ottawa and upper St. Lawrence valleys. The Sea drained from the Montreal-Ottawa area roughly 9,800 years ago (Farvolden and Cherry, 1988). Figure 1-2 illustrates the extent of the seawater incursion. The maximum depth of the Champlain sea in the Ottawa basin is estimated to be roughly 275m and occurred just north of Ottawa (Fulton, 1987). Subaqueous outwash, thin rhythmically bedded silts and clays and thick extensive marine

sediments were deposited in the Champlain Sea (Gadd, 1986). The glaciolacustrine sediments are not volumetrically important and are typically less than 2m thick grading upward into the marine sediments. The marine sediments are almost exclusively clays, sometimes rhythmically bedded and with silty interbeds, until the top of the sequence is reached where the regressing sea deposited a coarsening upward, prograding delta sequence which is terminated by coarse sands. Coarse fossiliferous gravels were also formed in littoral environments during the regressive phase (Rust, 1988). Maximum thickness of the Champlain Sea sediments is about 100m (Gadd, 1986). The fine-grained sediments of the Champlain Sea contain primarily quartz and feldspar, less than 30% phyllosilicates, less than 2% oxides, and a widely varying amount of carbonate depending on location and degree of weathering, suggesting that they are derived predominantly from glacially ground Precambrian material originating from the Canadian Shield (Torrance, 1988).

Torrance (1988) also studied the pore water salinity of Champlain Sea sediments and found that it varies from approximately its concentration at deposition to very low values depending on local factors which controlled the extent of salt removal by leaching or diffusion.

Hillaire-Marcel (1988) has documented the isotopic composition of biogenic carbonates born of the Champlain Sea. He has shown them to have wide ranges in isotopic compositions and reasoned that the high variability is due to the varying fluxes of meltwater from the retreating glaciers and from incursion of the sea such that there was sometimes a fresh water cap with salt conditions at depth. He recorded $\delta^{18}\text{O}$ values of -30 to -16 ‰

VSMOW and $\delta^{13}\text{C}$ values of -4 to +2.5 ‰ PDB in carbonate concretions and shell carbonates and related the isotopically enriched samples to deep water species.

Water flow to the Ottawa River during the retreat of the glaciers was highly variable and likely catastrophic at times. Lake Agassiz was the largest lake in North America during late glacial times and received the runoff of most of western Canada, an area of about 2,000,000 km². This water was periodically discharged through the Ottawa River basin, first at about 10,500 B.P. and for a duration of roughly 2,500 years, depending on the activity of the retreating glaciers (Teller, 1988). Teller (1988), estimates that 30,000 m³/s of meltwater and precipitation was added to the Ottawa River discharge during this period, cutting the channel through which the much smaller Ottawa River now flows.

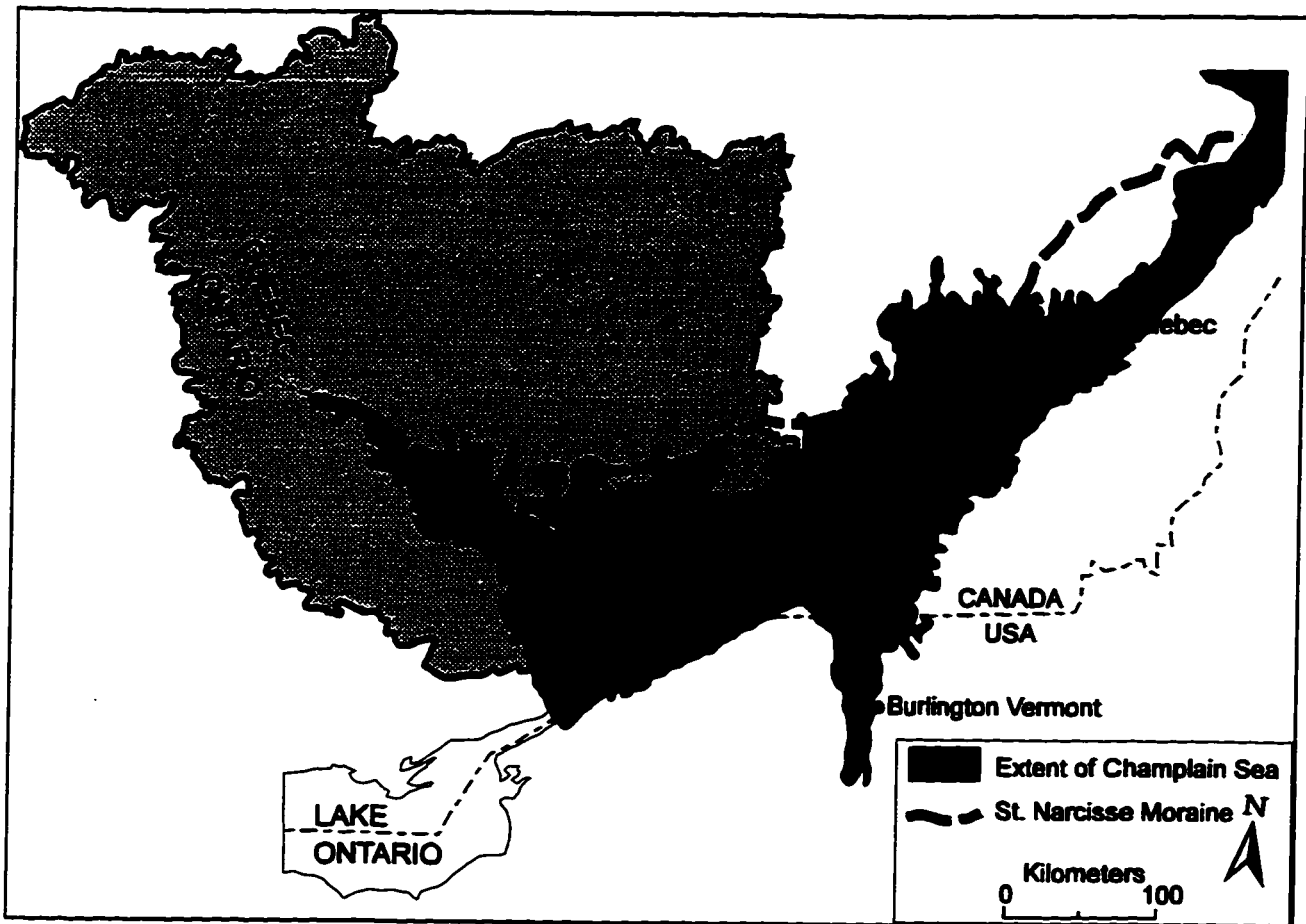


Figure 1-2: The extent of the Champlain Sea incursion into the modern Ottawa River basin (Champlain Sea data from Occhietti, 1989).

1.6.3d Post Glacial Deposits

Following the retreat of the last ice sheet and of marine waters, lacustrine, fluvial, paludal, eolian, and littoral sediments have been deposited in the basin (Occhietti, 1989; Gadd, 1986), although none of these is volumetrically important and most of them are confined to the lowlands region. Organic deposits, primarily peat, have accumulated in both the Canadian Shield and Lowlands regions. These deposits can be up to several meters thick (Terasmae, 1965).

1.7 HYDROGEOLOGY

1.7.1 Canadian Shield

Hydrographs of observation wells in the Precambrian part of the basin show that groundwater is recharged primarily from the annual spring snowmelt and from infiltration during cyclonic and frontal rainfall, with sporadic convective summer storms being of lesser importance (Farvolden et al., 1988). However, groundwater systems in the Canadian Shield portion of the basin, and for most of the Canadian Shield in general, have not been well studied because the region is sparsely populated and rich in good quality surface water. What is known about these systems comes primarily from studies within mines or from research by the Canadian Nuclear Fuel Waste Management Program (CNFWMP). The CNFWMP has four research sites in Ontario, one of these is in the Ottawa Basin, the Chalk River site.

Dugal et al. (1981) have separated the hydrogeology of the Canadian Shield into 3 regimes: (1) a local shallow fresh-water regime to depths of roughly 150m in which the flow is controlled by the surface topography, local lakes and swamps, and flat lying and high angle, typically sheared fracture zones; (2) an intermediate zone from 150 to 600m; and (3) a deep zone below 600m. Farvolden et al. (1988), generalized the characteristics of these regimes by stating that they are (1) strongly structurally controlled due to shear zones or dykes; and (2) flow within the structures has strong anisotropy due to shear movement, the intersection of fractures, and chemical deposition within the fracture planes. Other research, such as that by Wingrove et al. (1984) and Davison and Guvanase (1984), shows that flow systems exist in the bedrock and that, as for porous media environments, the water table is a subdued replica

of the topography and that the steep hydraulic gradients and low discharge suggest that hydraulic conductivity and effective porosity are low.

Farvolden et al. (1988) documented the history of hydraulic conductivity studies in the Canadian Shield and conclude that the previously believed log-linear decrease in hydraulic conductivity with depth only holds true in the shallow regime (roughly the top 100 to 400m) and that flat lying fracture zones, which can be found at various depths between surface and at least 1000m, are the major controls on regional flow. Further, the blocks of rock lying between the fracture zones are tight and no systematic flow pattern has been observed within them. The deep flow systems are influenced by regional slope but not by local topography.

1.7.2 Ottawa Lowlands

As already discussed in section 1.6, Geology, the lowlands are bounded by Precambrian rocks of the Canadian Shield and are composed of relatively undeformed Paleozoic sedimentary rocks consisting of limestones, dolostones, sandstones, siltstones and shales that reach thicknesses greater than 500m. This area is also richly endowed with glacial deposits from Pleistocene glaciations, such as moraines, outwash deposits, till, as well as glaciolacustrine and glaciomarine sediments, typically clays, such as those deposited by the Champlain Sea (see section 1.6.3 Quaternary Deposits). The tills and the Champlain Sea glaciomarine clays have typical total porosities of 0.4 and 0.6, respectively (Desaulniers and Cherry, 1987). Studies have estimated that groundwater contributions to base flow are about 40% of total stream flow in this region (Farvolden and Cherry, 1988). Cherry et al. (1976) and Sklash and Farvolden (1979) used oxygen isotopes to show that, contrary to earlier belief,

even storm runoff in headwater catchments is mostly water that existed in the catchment before the event and not water directly derived from overland flow.

The surficial clay-rich Quaternary deposits severely restrict the vertical flow of recharge. These deposits typically have a 3-6m thick surficial weathered zone containing many weathering features, such as secondary gypsum and calcite and oxidized oxide minerals. Fractures are vertical and ubiquitous and relic rootlets are common. The weathering profile is thought to have developed during the warm Alithermal climatic period between 9000 and 3000 years ago. Since that time the water table has risen and now exists within 1-2m of the surface in the weathered zone (Farvolden and Cherry, 1988). The hydraulic conductivity of the unweathered zone is low with values ranging from 4×10^{-5} to 9×10^{-6} m/d. The weathered zone has higher hydraulic conductivity due to fracturing and root holes. The hydraulic gradient in these deposits is generally downward with flow rates less than 1cm/a because the underlying material, fractured or porous bedrock or sandy deposits, act as regional ground water transmissive zones (Desaulniers and Cherry, 1987). Thus it is believed that groundwater velocities through the unweathered clay have been very slow during Holocene times.

Little evidence of regional groundwater flow is available for the Ottawa embayment of the St. Lawrence lowlands because most potable ground water occurs at shallow depths. Farvolden and Cherry (1988) suggest that local flow predominates and no regional component can be identified, implying that most groundwater will reach the Ottawa River as stream flow originating from local groundwater flow zones.

1.8 HYDRO-CHEMISTRY

Generally, there is a dearth of literature on the hydrogeochemistry of the Ottawa River itself and none which looks at the river in the context of its whole basin. There have been numerous studies on individual chemical parameters at specific localities within the river, such as those by Ramamoorthy and Rust (1976), who looked at mercury contamination and transport in the Ottawa River, Oliver (1973), who studied heavy metal levels in Rideau and Ottawa River sediments and Merriman and McRea (1982), who conducted a study within the immediate National Capital Region as a base line to detect changes caused by the installation of sewage treatment plants in nearby Quebec municipalities. However, these reports do not focus on the origin of the quality of the water in the basin context. There have been studies on the hydrology and regulation of the Ottawa River, such as those conducted by the Ottawa River Regulation Planning Committee (1980), Ottawa River Regulation Planning Board (1984) and the Ottawa River Engineering Board (1965). While these reports contain useful raw information, such as the size of reservoirs in the basin, they are political in nature and focus on satisfying the needs of the various parties using the river basin. Other reports by governmental bodies, such as the City of Ottawa Water Works Department (Bonk, 1958), the Ontario Water Resources Commission (1967), Canada Department of Energy, Mines, and Resources, Water Resources Branch (1968), and Ontario Hydro (1991), fall into the same category.

One report which addressed the chemistry of a significant portion of the river was produced in 1971 by the Ontario Water Resources Commission and the Quebec Water Board (1971). This report looked primarily at the municipal and industrial discharge into the river

and found that the greatest damage to water quality occurred from the discharge of substantial volumes of untreated pulp and paper mill wastes including solids (bark, wood chips, fibre), soluble organic compounds and organic mercurial compounds. The mercurial compounds were discharged from the E.B. Eddy Company in Hull and the Canadian International Paper Company in Gatineau. This discharge, combined with the discharge of raw sewage below Ottawa-Hull, depleted dissolved oxygen levels to below those necessary to sustain native fish species. The influx of nutrients from raw sewage increased the primary productivity of the river and this ultimately depleted levels of dissolved oxygen. However, 25 years later, following the recommendations of this report and others of its ilk (Environment Canada, Inland Waters Directorate, Water Quality Branch, 1986, 1989), much of the raw discharge to the river is now treated or substantially reduced, and water quality is much improved. For example, log driving on the Ottawa River was banned in the 1980s and on the Rivière Gatineau in the early 1990s, substantially reducing the Biological Oxygen Demand (BOD) load to these rivers. Today, all mill discharges receive primary treatment and many secondary treatment, the major population centres in Quebec have sewage treatment facilities, and the main sewage treatment facility for Ottawa-Carleton (Green Creek) has been upgraded to handle the pressures from an increasing population.

The World Health Organisation (1983) and Environment Canada (1993) have been collecting data on the chemistry of the Ottawa River and many other Canadian rivers for decades. However, at this time, the data for the Ottawa basin exists in raw form only. No review has been completed with the exception of the very brief summary by Hem et al. (1990), who use data from the mouth of the Ottawa River for their calculations of average runoff

chemistry of North America, and by Environment Canada, Inland Waters Directorate, Water Quality Branch (1986). Tables 1-2 and 1-3 list their findings, respectively.

Parameter	Minimum	Maximum
Nitrate + Nitrite (as NO_3)	0.25	0.97
Conductivity ($\mu\text{S cm}^{-1}$, 25°C)	30	605
pH	6.6	8.1

Table 1-2: Minimum and maximum values of nitrogen species, conductivity and pH for the Ottawa River, 1976 to 1982. Reproduced from Hem et al. (1990).

Parameter	Period of Record	Above Lake Temiskaming	Temiskaming Dam	Carillon Dam
Na	79-83	1.24	1.22	2.92
K	80-83	0.81	0.87	1.14
Ca	79-83	4.06	6.76	9.09
Mg	79-83	1.27	1.90	2.34
Cl	81-83	0.89	1.28	3.36
Alkalinity (as CaCO_3)	79-83	6.42	15.4	23.8
SO_4	79-83	8.02	9.14	9.93

Table 1-3: Average concentration of major ions in the Ottawa River (mg/l) (adapted from Environment Canada, Inland Waters Directorate, Water Quality Branch, 1986).

A more detailed summary of the water chemistry of the Ottawa basin, calculated from historical data, is presented in chapter 5.

Merriman (1987) reported on bottom sediment quality of the Ottawa River and Merriman and Metcalfe (1988) report on pesticide distribution in the lower Ottawa River. Their work is not directly utilized in this study but has obvious links and is worth mentioning.

2 FIELD AND LABORATORY INVESTIGATIONS

2.1 SAMPLING METHODOLOGY

Samples were taken along the entire length of the Ottawa River and from the mouths of its major tributaries at as close to one instant in time as possible for a total of three times, twice during low water stand in September of 1991 and 1992 and once during high water stand in May of 1992. During the first sampling campaign, 34 samples were collected, 16 from the Ottawa River at a spacing of 50-100km, and 18 from major tributaries. During the second sampling campaign in the spring of 1992, 35 samples were collected, 16 from the Ottawa River, 19 from major tributaries. Some minor adjustments to the sampling localities were made after viewing the preliminary results of the first sampling campaign.

A third field campaign was completed in the fall of 1992. This field campaign was not part of the original research plan, yet, after fine tuning field analytical techniques and in some instances adopting new techniques, it appeared desirable to repeat the spring 1991 campaign in order to compare results. 16 samples from the Ottawa River and 3 tributary samples were deemed sufficient for these follow up purposes. Figure 2-1 shows the sampling localities for all three sampling campaigns.

Vertical and longitudinal mixing concerns exerted a secondary influence on the choice of sample localities. Sanders et al. (1983) state that rivers are usually sufficiently shallow and turbulent so that vertical homogeneity is quickly attained below an influx of new material. Lateral homogeneity is attained more slowly. Thus wide, swift-flowing rivers may not be completely mixed for many kilometers below the influx point. Large inflows from tributaries

can take up to 16km to mix completely in the Columbia River (Hem, 1985) and up to 150km in the "longitudinally stratified" St. Lawrence River (Yang et al., 1996). Sampling localities were chosen to minimize mixing concerns. Fortunately, areas where rivers are well mixed and where they are easily sampled are typically coincident. Bridges and ferry crossings, which make excellent sampling locations, are common where the river is narrow, swift and turbulent and hence well mixed. Below hydroelectrical generating stations the water is usually well mixed and there usually exists some infrastructure to allow sampling.

The literature is rife with methods for sampling and analysing individual water aliquots for a plethora of aqueous chemical species, yet there is a dearth of discussions on strategies for sampling a river in its entirety. Personnel working at the Centre St. Laurent in Montreal sampled the St. Lawrence River from headwaters to mouth moving at the same speed as the water mass (Lum, 1991). This allows the evolution of one water mass through space to be tracked. Due to field logistics, including the need to carry out a simultaneous sampling campaign on the St. Lawrence River, and difficulty of gaining access to parts of the Ottawa River basin, the Centre St. Laurent sampling strategy was modified for this study. The sample procurement route is shown in Figure 2-1.

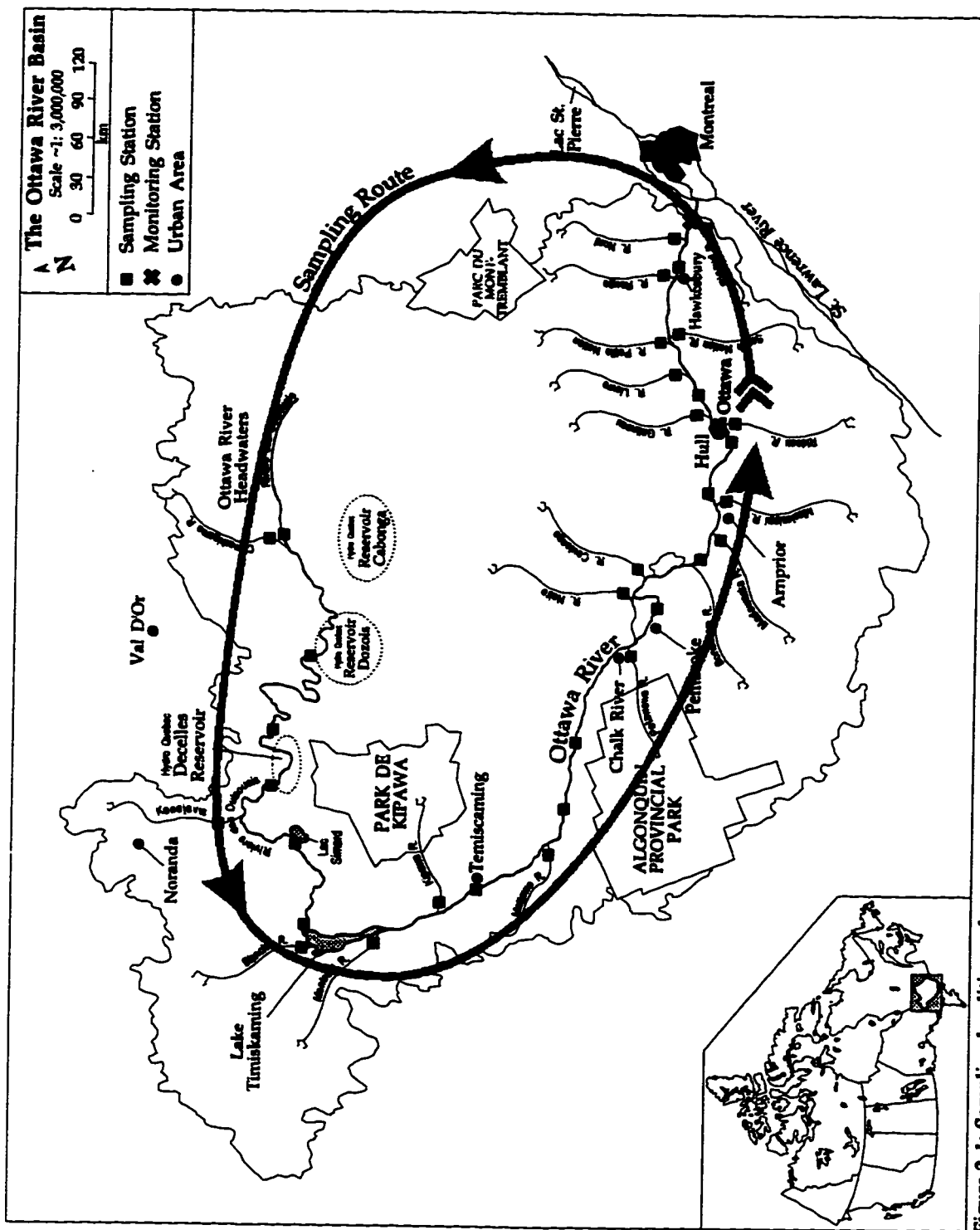


Figure 2-1: Sampling localities and procurement route.

2.1.1 The Monitoring Station

In addition to the "whole river" sampling campaign, water was taken from one location near the mouth of the Ottawa River once a month for 13 months adding a temporal perspective to the study and allowing the nature and timing of the transition from high to low water stand to be determined. The generating station at Carillon was chosen as the location for the monitoring station because (1) it is at the mouth of the Ottawa River and thus samples taken here should provide a signal of the whole basin; (2) at this point the river is well mixed; (3) the ferry that crosses the river there is ideal for sampling; and (4) the turbulence caused by the generating station 1 km upstream causes the river to remain unfrozen at Carillon all year (see Figure 2-1 for location).

2.2 SAMPLE PRESERVATION

After being filtered through a 0.45μ Millipore membrane, duplicate samples were collected and stored at 4°C for chemical and isotope analysis. Samples collected for anion analysis needed no further treatment. The samples for determination of cations and Sr isotopes were acidified with strong HNO_3 . For carbon isotopes, samples were collected in brown glass bottles with air-tight polycone caps and poisoned with HgCl_2 to eliminate bacterial growth. For sulfur isotopes, each sample was treated with HCl and BaCl_2 to precipitate BaSO_4 , which was then collected by filtering through 0.45μ Millipore ashless filter paper. Figure 2-2 illustrates the analytical and preservation procedures used in the field and laboratory.

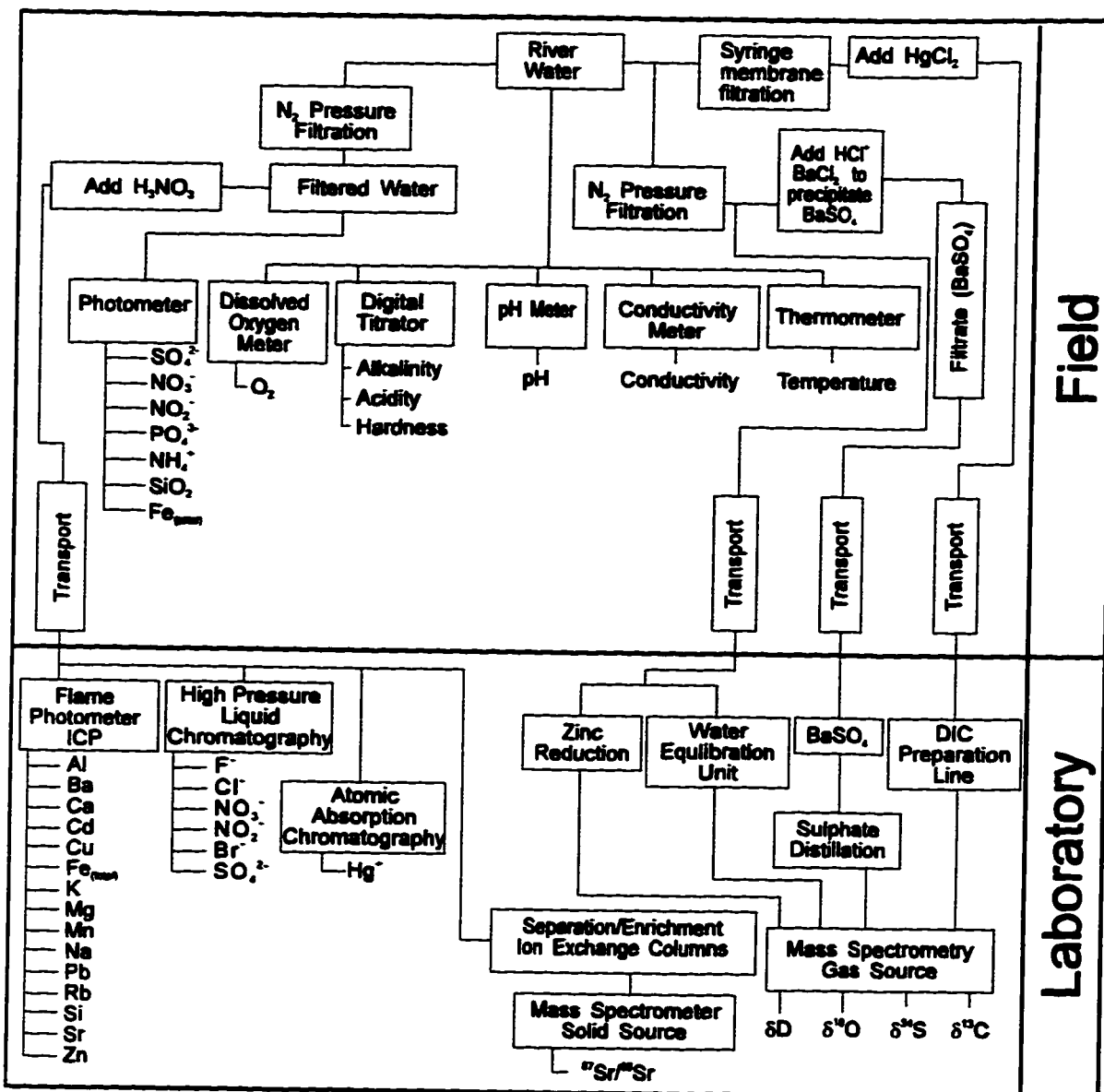


Figure 2-2: preservation and analytical procedures used in the field and laboratory.

2.2.1 Field Versus Laboratory Measurements

It is more convenient, less time consuming and usually more accurate to measure water chemistry parameters in a well equipped laboratory; nevertheless, parameters which are unstable or are easily contaminated must be measured immediately in the field. Table 2-1 lists

the required containers, preservation techniques and holding times recommended by the US Federal Register (HACH Company, 1993).

No.	Parameter	Container	Preservation	Maximum Holding Time
1	Alkalinity	p,g	none	48 hours
2	Ammonia	p,g	cool, 4°C, H ₂ SO ₄ to pH<2	28 days
3	Chloride	p,g	None required	6 months
4	Mercury	p,g	cool, 4°C, HNO ₃ to pH<2	28 days
5	Trace metals & rare earth elements	p,g	cool, 4°C, HNO ₃ to pH<2	6 months
6	Nitrate	p,g	cool, 4°C	48 hours
7	Orthophosphate	p,g	cool, 4°C	48 hours
8	Phosphorous total	p,g	cool, 4°C, H ₂ SO ₄ to pH<2	28 days
9	Silica	p	cool, 4°C, HNO ₃ to pH<2	28 days
10	Sulphate	p,g	cool, 4°C, HNO ₃ to pH<2	48 hours
11	Carbon isotopes ($\delta^{13}\text{C}$)	g	cool, 4°C, poison with HgCl ₂	6 months
12	Hydrogen isotopes (δD)	p,g	none required	indefinitely
13	Oxygen isotopes ($\delta^{18}\text{O}$)	p,g	none required	indefinitely
14	Strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$)	p,g	cool, 4°C, HNO ₃ to pH<2	6 months
15	Sulfur isotopes ($\delta^{34}\text{S}$)	p,g	precipitate as BaSO ₄ immediately and keep precipitate	indefinitely

Table 2-1: Required containers, preservation techniques and holding times; p = polyethylene, g = glass (HACH Company, 1993).

2.2.2 Container Preparation

Appropriate containers were used to collect samples for different parameters. Table 2-2 lists the container type and size used to collect different parameters. All containers were scrupulously cleaned before use following the cleaning procedure outlined in the Nalgene Use and Care Guide (1994), which was based on a procedure developed and tested by the University of Rhode Island Graduate School of Oceanography (Moody and Lindstrom, 1977),

or by the procedure recommended by Environment Canada (Environment Canada, 1974), as follows:

1. wash in mild non-abrasive detergent and rinse with tap and then distilled water.
2. soak in chromic acid for 4 hours and rinse in distilled water 3 times.
3. soak in 1M HNO_3 for 8 hours and rinse 4 times in de-ionized water.
4. soak in de-ionized water for at least 24 hours.

Parameter to be preserved	Type of Container	Treatment	Maximum preservation Time
Anions	Nalgene - 100ml	Filter (.45 μ) & cool to 4°C	2 months
Cations	Nalgene - 250ml	Filter (.45 μ), acidify with HNO_3 & cool to 4°C	6 months
Oxygen & Hydrogen isotopes	Nalgene - 100ml	Filter (.45 μ) & cool to 4°C	Indefinite
Carbon isotopes	Brown glass - 100ml with polycone caps.	Filter (.45 μ), poison with HgCl_2 & cool to 4°C	6 months
Strontium isotopes	Nalgene - 50ml	Filter (.45 μ), acidify with HNO_3 & cool to 4°C	6 months
Sulfur isotopes	Glass vial to hold ashless filter paper and filtrate.	Filter (.45 μ), lower pH to 2 with HCl , precipitate BaSO_4 by adding BaCl_2 solution, and collect filtrate.	Indefinite
Trace & rare earth elements	Nalgene - 250ml	Filter (.45 μ), acidify with HNO_3 & cool to 4°C	6 months

Table 2-2: Container types and sample preservation.

2.3 SAMPLING PROCEDURE

2.3.1 Measured Parameters

The initial field campaign was used both for collecting data and for reconnoitering field analytical techniques and their necessity. All sensitive parameters were measured in the field until the viability of preserving them and measuring them in the laboratory was tested. The results of the first campaign field and laboratory analyses were used as a basis for subsequent field season strategies. Some parameters measured in the field in the fall of 1991 were discontinued in subsequent field campaigns for one of the following reasons: (1) an acceptable

method of preservation was determined and the parameters were therefore measured at a later date in the laboratory more conveniently and typically with more accuracy; (2) the parameter was undetectable at all localities; (3) the parameter could be calculated from other parameters.

Dissolved oxygen was initially measured by titration and subsequently by electrode. Table 2-3 shows the parameters measured and techniques used in the field for different campaigns.

Parameter	Fall 1991	Spring 1992	Fall 1992	Monitoring Station 93/94
Temp °C	e	e	e	e
pH	e	e	e	e
Conductivity mS/cm	e	e	e	e
Alkalinity	t	t	t	t
Acidity	t	*c	*c	*c
Hardness	t	*c	*c	*c
Dissolved Oxygen (DO)	t	e	e	e
Ammonia (NH ₄)	p	**	**	**
Nitrate (NO ₃)	p	p	p	*
Nitrite (NO ₂)	p	**	**	**
Phosphate (PO ₄)	p	*	*	*
Sulphate (SO ₄)	p	p	p	p
Ferric Iron (Fe ₂ ⁺)	p	**	**	**
Total Iron	p	*	*	*
Silica (SiO ₂)	p	*	*	*
Chloride (Cl)	t	*	*	*
Cyanide (CN)	p	**	**	**

Table 2-3: Parameters measured during the field campaigns. e = measured by electrode, p = measured by solution spectrophotometer, t = measured by titration, * = preserved and measured in the lab, ** = discontinued due to undetectability, *c = subsequently calculated.

2.3.2 Collecting the Sample

River water samples were collected from bridges, hydroelectric dams, barrages, and ferries at a depth of 2m and at a lateral position where the water was most likely to be well mixed. Generally the centre of the rivers satisfied these conditions. Samples were collected using a narrow-mouthed glass bottle attached to a heavy metal retort stand (sampling iron)

and with a teflon groundwater bailer. The sampling iron was rapidly lowered to a depth of 2m, preventing the collection of any surface water and floating materials (litter, oils, etc.) and then slowly jiggled between depths of 2 and 4 m producing a moderately "depth-integrated" grab sample. Once full, the iron was raised, the glass bottle tightly capped and removed from the apparatus. The teflon bailer was also lowered to a depth of 2m and jiggled to allow through flow for several minutes. When the bailer is raised, it automatically seals itself from the atmosphere preventing contamination from atmospheric oxygen and carbon dioxide. The bottles and bailer were then taken nearby where the field analyses were performed immediately.

There are two main types of water samples typically collected by water quality surveys, grab-samples and composite-samples, each having different uses (Hem et al., 1990). Grab-samples characterize water quality at a particular time, and provide information about minimum and maximum concentrations during the history of the sampling campaign. Composite samples are collected over a period of time and thus provide an estimate of average water quality over the period of sampling. Composite samples cannot detect changes in water quality that occur during the period of time represented by the composite sample. In this study, it would have been best to use a composite sample which represents a time interval slightly less than the interval being investigated (on the order of days) rather than a grab sample which represents a time interval (15 minutes) much less than the interval of interest. For this study, as for many water surveys, for practical reasons such as cost and field logistics, it was only possible to collect grab-samples. These water quality measurements should therefore be, to some degree, considered of reconnaissance nature. However, Taylor and

Hamilton (1994) assessed cross-channel and diurnal variation of solutes within sites, using data collected over 25 years at numerous sites throughout the Saskatchewan River basin (365,000 km², a similar scale as the Ottawa River basin). Their results showed that the coefficient of variation (CV) of multiple samples taken within 1 day at four sites was usually less than 5% (analytical error is often of this magnitude) and always less than 10%, suggesting that daily mean concentration may be reliably estimated from a single grab sample. They also concluded that cross-channel variations were unlikely to be significant, except where tributary inflows have not yet mixed with the flow of the main river. To further validate the meaningfulness of data from this study, average concentrations of major dissolved species from this study were compared with those based on a much greater number of composite samples from the Envirodat water quality database (Environment Canada, 1993) taken over a decade. Table 2-4 lists the averages. The two datasets strongly agree. Some differences are expected since the sampling campaigns were not synchronous. The databases and their analyses are discussed further in chapters 3 and 5.

	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	pH
	$\mu\text{mol/l}$							
River water (this study)	139.0	19.8	94.6	253.5	117.3	91.9	5.9	7.0
River water (Environment Canada, 1993)	127.0	26.0	96.4	233.0	96.3	100.8	3.3	7.1

Table 2-4: Average concentration of the Ottawa River at its mouth. Data from this study are averaged from 15 samples taken during 1993-94; data from Environment Canada (1993) are averaged from a maximum of 221 samples taken during 1978-88 for pH and a minimum of 24 samples taken during 1979-82 for Na⁺. For more details on the Environment Canada data, see appendix C, table 1.

2.3.3 Field Analytical Equipment

Table 2-5 lists the field analysis equipment used in this project.

Procedure	Manufacturer	Name of Equipment	Model Number
Solution Spectrophotometry	HACH	Spectrophotometer	DR/2000
Titration	HACH	Portable digital titrator	16900-01
pH	HACH	Portable Hach one pH meter	43900-00
Dissolved Oxygen	Orion Research	O ² oxygen electrode	97-08
General filtration (.45m)	Custom	Positive pressure fritted glass membrane filter	-
Conductivity	HACH	Portable Hach one conductivity meter	
Carbon isotope filtration (.45µ)	Micron Separations Inc.	Syringe tip membrane filter	DDN04T2550

Table 2-5: Field equipment.

2.4 FIELD ANALYSES

2.4.1 Titrations

Titration were done with a HACH digital titrator (see Table 2-5). With this titrator a main screw drives a plunger which forces a solution from a titration cartridge in a precisely controlled flow. The titration solution is dispensed into a volume of sample containing a colour indicator. When the endpoint colour is reached, the digital readout in the counter window and a multiplier yield the concentration of the desired parameter.

Accuracy is rated at $\pm 1\%$ or better for a titration of more than 100 digits and ± 1 digit for titrations less than 100 digits (one digit represents the smallest volume dispensed by the titrator). In this project, an appropriate titration solution concentration was chosen to ensure titrations of more than 100 digits thus ensuring an accuracy of $\pm 1\%$.

Titration solutions purchased from HACH are rated at $\pm 0.5\%$ normality. Replacement solutions made in the lab were tested repeatedly on samples of known concentration until the same accuracy was attained. Accuracy was checked in the field by repeating titrations on various dilutions of the parameter being investigated. Interferences for various titrations exist, but in general, conditions under which interference would be a concern were not encountered. Water used for titrations, except for the dissolved oxygen titration, was taken from the

sampling iron. Initially, all water was filtered at 0.45μ before titration, but it was discovered through testing that unless turbid conditions were encountered initial filtering made no difference to the titration results.

2.4.2 Titration for Acidity

Bromphenol blue (pH end point 3.7) or phenolphalein (pH end point 8.3) indicator were used to titrate the sample with sodium hydroxide to a colourimetric end point. Because bromphenol blue gives a better end point, methyl orange was not used as the indicator. Titration to pH 3.7 yields strong mineral acidity also referred to as methyl orange acidity. Titration to pH 8.3 yields total acidity and includes weaker acid species as well as the strong ones. The results are expressed in mg/l calcium carbonate (CaCO_3) at the specified pH.

In this project, pH below 3.7 was not encountered and so the bromphenol blue (pH end point 3.7) titration was not necessary. In fact, after the first field campaign, acidity was no longer measured in the field (see Table 2-3) because it could be calculated from the total alkalinity, pH, and major ion concentration using Equation 2-1. Aluminum and iron are examples of hydrolysable cations.

$$\text{Acidity} = m_{\text{H}^+} - m_{\text{HCO}_3^-} + \text{hydrolyzable cations} - \text{hydrolyzable anions}$$

Equation 2-1 (Drever, 1988)

2.4.3 Titration for Alkalinity

Samples were titrated for alkalinity with sulphuric acid to a colourimetric end point corresponding to a specific pH. Phenolphalein alkalinity is determined by titration to a pH of 8.3, and indicates the total hydroxide and one half the carbonate present. None of the samples collected had a pH greater than 8.3 and so phenolphalein alkalinity was consistently equal to

zero. Total alkalinity is determined by titration to a pH between 3.7 and 5.1 and includes all carbonate, hydroxide and bicarbonate species. Table 2-6 outlines how the appropriate pH endpoint is chosen. In this study, a pH endpoint of 4.8 was most common.

Sample Composition	End point
Alkalinity about 30 mg/l	pH 5.1
Alkalinity about 150 mg/l	pH 4.8
Alkalinity about 500 mg/l	pH 4.5
Silicates or phosphates present	pH 4.5
Industrial waste or complex system	pH 3.7

Table 2-6: Recommended pH end points for titration of total alkalinity under different conditions (HACH Company, 1992).

2.4.3a Interferences

Highly coloured or turbid samples can mask the colour change at the end point of the titration but this problem was not encountered. Chlorine can interfere with the behaviour of the indicators. To prevent this sodium thiosulphate is added. This was done to samples with the highest chloride concentrations to determine if chloride was indeed interfering with the results. Any differences detected fell well within analytical error.

2.4.4 Titration for Chloride

Samples were titrated for chloride with mercuric nitrate [$\text{Hg}(\text{NO}_3)_2$] using diphenylcarbazone indicator to a colourimetric end point. Titrations for chloride were suspended after the second field campaign because preservation and determination in the laboratory using an HPLC were deemed more reliable and accurate.

2.4.4a Interferences

Chromate, ferric iron, sulphite, iodide, and bromide when present in excess of 10 mg/l can interfere with this method. These conditions were not encountered in this study.

2.4.5 Titration for Total Hardness

Samples were titrated with EDTA solution using ManVer 2 Hardness indicator after being buffered to a pH of 10.1. Titrations for hardness were suspended after the first field campaign because preservation and determination in the laboratory by determining the concentration of Ca^{2+} and Mg^{2+} with an ICP photometer were deemed more reliable and accurate.

2.4.6 Titration for Dissolved Oxygen

Dissolved oxygen was measured by titration for the first field campaign. Water was collected by placing a 60 ml BOD bottle and its ground glass stopper into a 1 l jar and lowering the jar into the river along with the sampling iron. The apparatus is held underwater at a depth of 2m for 3 minutes to allow complete equilibration of the water in the 60 ml BOD bottle and its surroundings. The lid to the jar has only a small opening which eliminates the intake of water close to the surface and it exposes only limited surface area to atmospheric contamination when the apparatus is retrieved from the river. The BOD bottle is completely isolated from the atmosphere by submergence within the jar. When the apparatus is retrieved, the jar is opened and the ground glass stopper is inserted into the BOD bottle, as quickly as possible, while the BOD bottle is still submerged.

Samples are treated with manganous sulfate and alkaline iodide-azide reagent to form an orange-brown precipitate. Upon acidification of the sample, this floc reacts with iodide to produce free iodine as I_3^- , in proportion to the oxygen concentration. The iodine is then

titrated with sodium thiosulphate to the starch-iodide end point and the results are reported in mg/l.

This procedure was suspended after the first field campaign because dissolved oxygen was subsequently measured with an electrode.

2.4.7 Determination of Dissolved Oxygen by Electrode

During the second and third sampling campaigns as well as for the monitoring station, dissolved oxygen was measured with an ATI Orion Research model 97-08 Oxygen Electrode (1992). It is a polarographic device consisting of a pair of polarized silver electrodes and an electrolyte separated from the sample by a gas-permeable membrane. Oxygen diffuses across the membrane and is reduced to hydroxyl ions at a silver cathode. The electrons necessary for this reaction to occur are provided by a silver anode and thus the current flowing between anode and cathode is proportional to the level of oxygen outside the membrane. Equations 2-2 and 2-3 summarize this process:



The meter displays dissolved oxygen in parts per million ± 0.05 ppm or 2% of reading (whichever is larger) after compensating for temperature factors.

A Biological Oxygen Demand (BOD) bottle, transformed into a flow through cell and connected to a collapsible teflon bailer which isolates itself automatically from the atmosphere, was used in conjunction with the Orion electrode to measure dissolved oxygen. Measurement was performed as quickly as possible after the sample was procured. The water was not pre-treated in any manner before measurement commenced.

2.4.8 Determination of Conductivity

Conductivity was measured with a portable HACH one conductivity meter (HACH Company, 1993) which uses a standard conductivity electrode. The water was not pre-treated in any manner before measurement commenced. Conductivity is reported in ms/cm^2 .

2.4.9 Determination of pH and Temperature

pH and temperature were measured with a portable HACH One pH Meter, model 43800-00. The meter uses a thermistor, glass electrode, silver-silver chloride reference element and a continually renewing liquid junction, the latter replacing the conventional ceramic or fibre porous junction. This free diffusion junction has been shown to give more reliable pH readings than conventional electrodes because of the stability of the junction potential (HACH Company, 1993; Illingworth, 1981; Davison and Woof, 1985).

Measurements of pH and temperature were obtained in the following manner:

1. pre-condition the electrode by soaking it in a solution of similar ionic strength as the sample;
2. calibrate the meter with buffer solutions of pH 4 and 7 or 7 and 10, depending on the pH of the sample;
3. thoroughly rinse the electrode in sample;
4. measure the pH of fresh sample several times until a consistent reading is obtained; Fresh sample was acquired from a flow through apparatus connected to a collapsible teflon bailer which was isolated from the atmosphere. The sample was not pre-treated in any manner before measurement commenced;

5. Test the accuracy of the meter: measure the pH of the pH 7 buffer solution. If this measurement falls within ± 0.05 pH then the reading is kept, otherwise the procedure is repeated;
6. temperature of the solution is recorded initially and at the completion of the procedure if there is a difference.

This seemingly elaborate technique was deemed necessary after inconsistent pH readings were obtained using the standard methods outlined in the HACH manual.

2.4.10 Photometric Analysis

A HACH DR/2000 Spectrophotometer was used for the measurement of ammonia (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), ferric iron (Fe^{2+}), total iron (Fe_{tot}), silica (SiO_2), and cyanide (CN^-) during the first field campaign. The measurement of all parameters except nitrate (NO_3^-) and sulphate (SO_4^{2-}) was discontinued in subsequent field campaigns due to either concentrations below photometer detection limits, or due to the development of a preservation technique such that the parameter could be measured at a later time in the laboratory.

The water used for photometric analyses was taken from the sampling iron and was passed through a $.45\mu$ filter prior to analyses. Procedures for determining parameters can be found in the HACH Procedures Manual (1993).

2.4.10a Precision

Precision was tested by repeating analyses of 5 dilutions of a standard solution for the given parameter. Each dilution was measured 10 times. In most cases the error was less than $\pm 1\%$ and in all cases $\pm 5\%$. The higher error was attained only on the most diluted aliquots.

2.4.10b Accuracy

The standard additions technique was used to test the accuracy of the instrument. A sample of Ottawa River water is measured for the desired parameter. A small amount of standard solution is added to the sample and it is measured again. The increase in the measured parameter should equal exactly the amount of the component added. If this is true, one can conclude that the first measurement is also true and that the instrument and reagents are operating correctly. If the second analysis is spurious, then it is concluded that the first measurement is also incorrect and a decision tree (HACH Company, 1993), using a type of ANOVA, is used to isolate the problem.

2.5 LABORATORY ANALYSES

In the laboratory major cations were analyzed by a Thermo Jarrell Ash Atomscan 25 Argon ICP (AES). The D/H isotope ratio was determined by analyzing H_2 gas on an automated double collector VG 602D mass spectrometer. Water was converted to hydrogen by oxidation with hot zinc. The $^{18}O/^{16}O$ ratio was determined by equilibrating a small amount of CO_2 with 3ml of sample and analyzing the resulting CO_2 on a triple collector VG SIRA 12 mass spectrometer. The $^{13}C/^{12}C$ ratios were determined by mass spectrometry (VG SIRA 12) on CO_2 gas liberated by adding concentrated H_3PO_4 to the samples under vacuum. Sulfur isotopes were determined by combusting $BaSO_4$ under vacuum with an oxidizing agent (CuO) to release SO_2 , which was then measured on a triple collector VG SIRA 12 mass spectrometer. The δD , $\delta^{18}O$, $\delta^{13}C$ and $\delta^{34}S$ are reported relative to VSMOW, Chicago PDB, and to Canyon Diablo Troilite, respectively, with a precision of $\pm 0.1\%$. All these measurements were carried out at the Department of Geology, University of Ottawa. Sr

isotope measurements were determined on a five collector Finnigan MAT 262 solid source mass spectrometer at the Institute for Geology, Ruhr University, Bochum (Buhl et al., 1991; Diener et al., 1996).

2.6 RESULTS

The results of chemical and isotopic measurements can be found in Appendix A. The partial pressure of CO_2 and the saturation index of calcite and dolomite in the river were calculated using the procedures discussed in chapter 5 and with the WATEQ computer program (Truesdell and Jones, 1974) for comparison. Differences were minimal and always less than analytical error. The concentration of dissolved inorganic carbon (DIC) was calculated from alkalinity and pH (Skirrow, 1975).

3 THE PHYSICAL-CHEMICAL DATABASE

3.1 THE GIS STUDY AREA

SPANS GIS (TYDAC Technologies Inc., 1995a), SPANS EXPLORER (TYDAC Technologies Inc., 1995b), and TYDIG (TYDAC Technologies Inc., 1995c) were the GIS software used for this project.

3.1.1 Projection

The details of the projection used in the GIS study area for this project are:

Lambert Conformal Conic

Ellipsoid 7 1866, Clarke, North America.

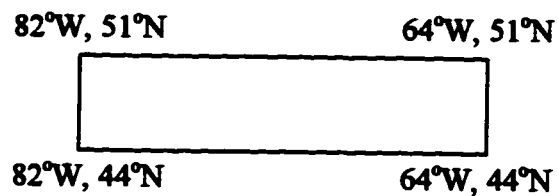
True Origin 95°W, 49°N

First Parallel 49°N

Second Parallel 77°N

3.1.2 Extents

The geographical extents of the four corners of the SPANS study area are:



3.1.3 Resolution

For the Ottawa River basin study area, the maximum attainable cell resolution in a SPANS quadtree raster is:

$$1 \text{ cell} = 61 \times 61 \text{m (quad level 15)}$$

The quad level refers to the exponent in a base 2 system such that a quad 15 quadtree raster would have a maximum number of cells of $(2^{15})^2$; a quad 13 quadtree raster would have a maximum number of cells of $(2^{13})^2$.

To avoid unnecessary computer processing, a quad level of 13 was used. Considering the resolution of some of the source data for this project, such as the Etopo5 dataset discussed below which has a resolution of 1 point every 5 arc minutes (1 point every 9277m along lines of longitude; 1 point every 9277m along the equator; 1 point every ~6250m along a line of latitude at 48°N; and 1 point every ~2800m along a line of latitude at 72°N), a quad level of 13, which has a raster cell size of 244x244m in the study area, provides sufficient resolution to represent the data accurately. The only advantage in using a higher quad level would be for display in a highly magnified window. In such a window, contours would be smoother but no more precise. This may be desirable for large format output.

3.2 MANUAL DIGITIZING

3.2.1 Bedrock Geology

The bedrock geology for the Ottawa River Basin was simplified and manually digitized using TYDIG (TYDAC Technologies Inc., 1995c) from Baer et al. (1971). Figure 3-1

illustrates the results. The geology of the Ottawa River basin is described in detail in chapter

1.

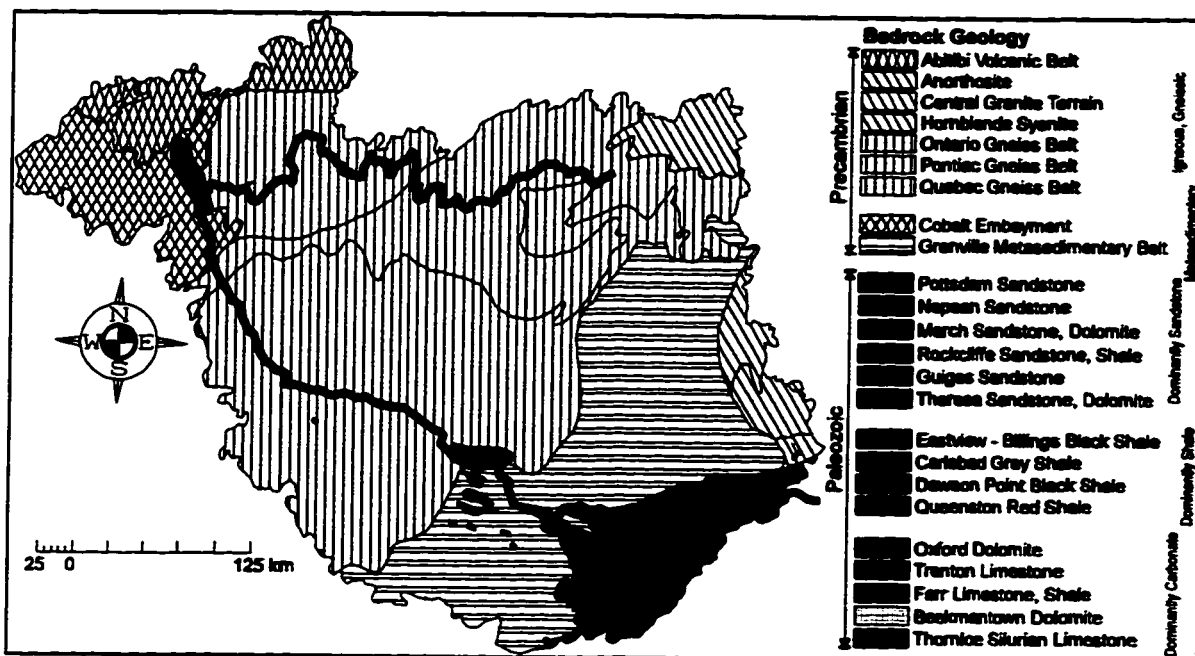


Figure 3-1: Bedrock geology of the Ottawa River basin (adapted from Baer et al., 1971).

3.2.2 Watershed Boundaries and Hydrology

Watershed boundaries and basic hydrology for the Ottawa River Basin were manually digitized using TYDIG (TYDAC Technologies Inc., 1995c) from Environment Canada's Active Hydrometric Stations map series (Environment Canada, 1988; 1986). The boundaries are also available in Environment Canada's Environmental Information System (EIS) database (Environment Canada, 1993) but attributes for the polygons are missing and the resolution of the boundaries is rather low. Figure 3-2 illustrates the major watershed boundaries and basic hydrology of the Ottawa River basin. The total area of the Ottawa River basin was previously estimated to be 146,000 km² (Canada Department of Northern Affairs and Natural Resources, Water Resources Branch, 1962). Calculations based on the digitized watershed boundaries yield an area of 149,000 km². This value is also obtained by analyzing the data in Environment

Canada's EIS database. Therefore, the new estimate of 149,000 km² will be used as the total area of the Ottawa River basin in this study.

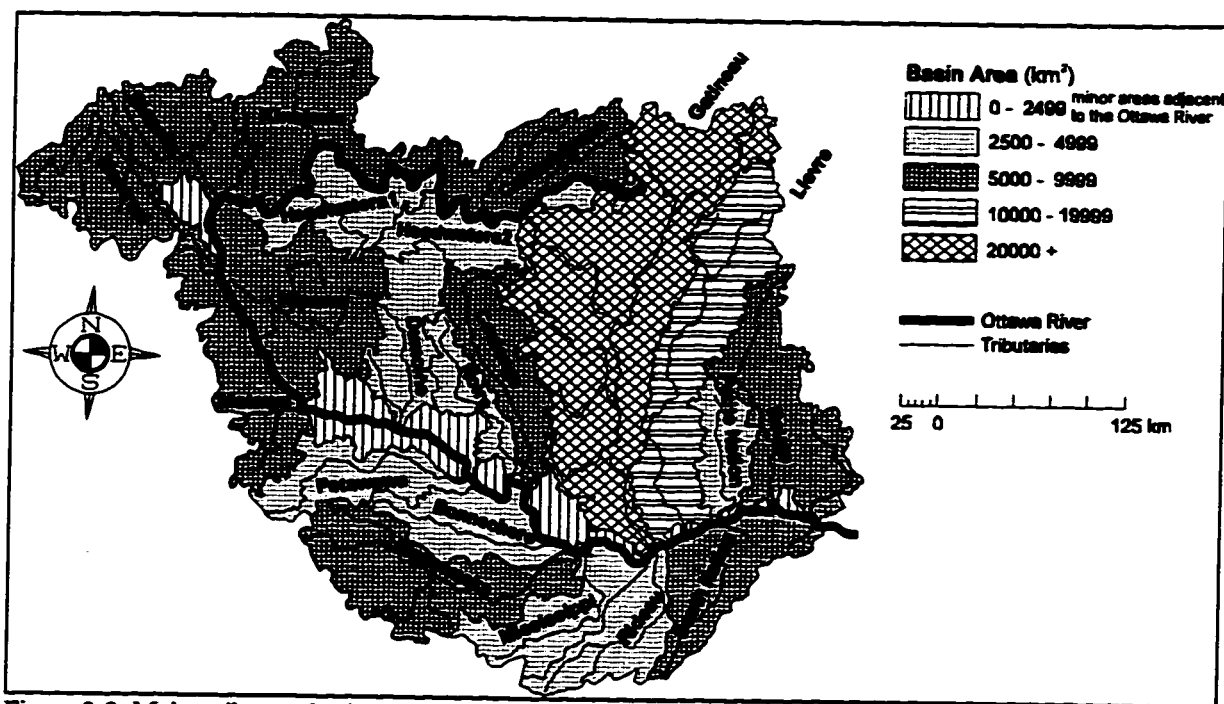


Figure 3-2: Major tributary basins classified by size and basic hydrology of the Ottawa River basin.

3.2.2a DCW vector Files

The Digital Chart of the World (DCW) is a comprehensive 1:1,000,000-scale vector basemap of the world. It consists of cartographic, attribute, and textual data stored on CD-ROMs. The primary source for the database is the US Defense Mapping Agency (DMA) Operational Navigation Chart (ONC) series. The DCW database is topologically structured and is therefore suitable for use in Geographic Information Systems (GIS).

Detailed hydrology (lakes and streams) as well as political boundaries and roads were extracted from this database, nevertheless, despite the topological nature of the DCW, a considerable amount of editing was necessary to bring the data into SPANS and once imported the topological nature of the data was too poor to be of any use.

3.2.3 Population Distribution

Population statistics were obtained from Statistics Canada (1991) and summarized into rural, urban, and total population per tributary subbasin (Figure 3-3, Figure 3-4, and Figure 3-5).

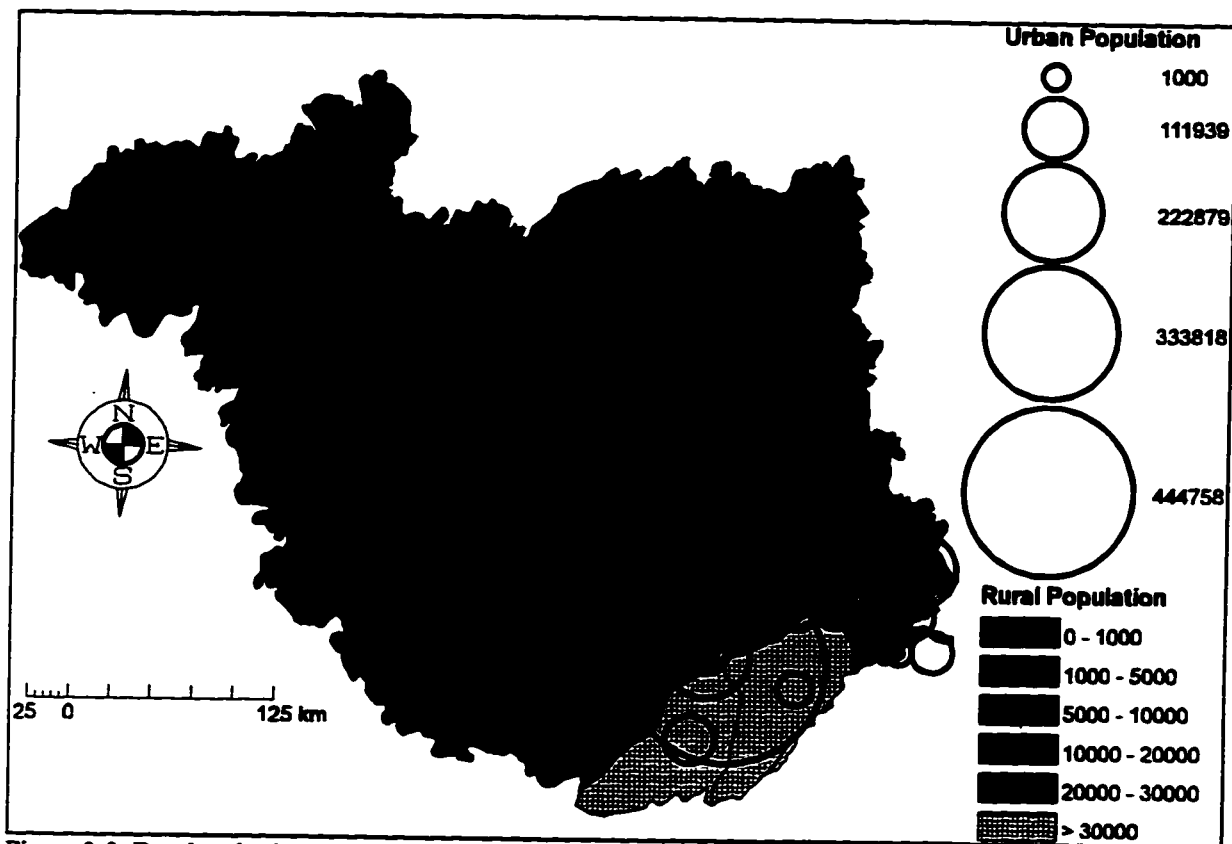


Figure 3-3: Rural and urban population per tributary basin (from Statistics Canada, 1991)

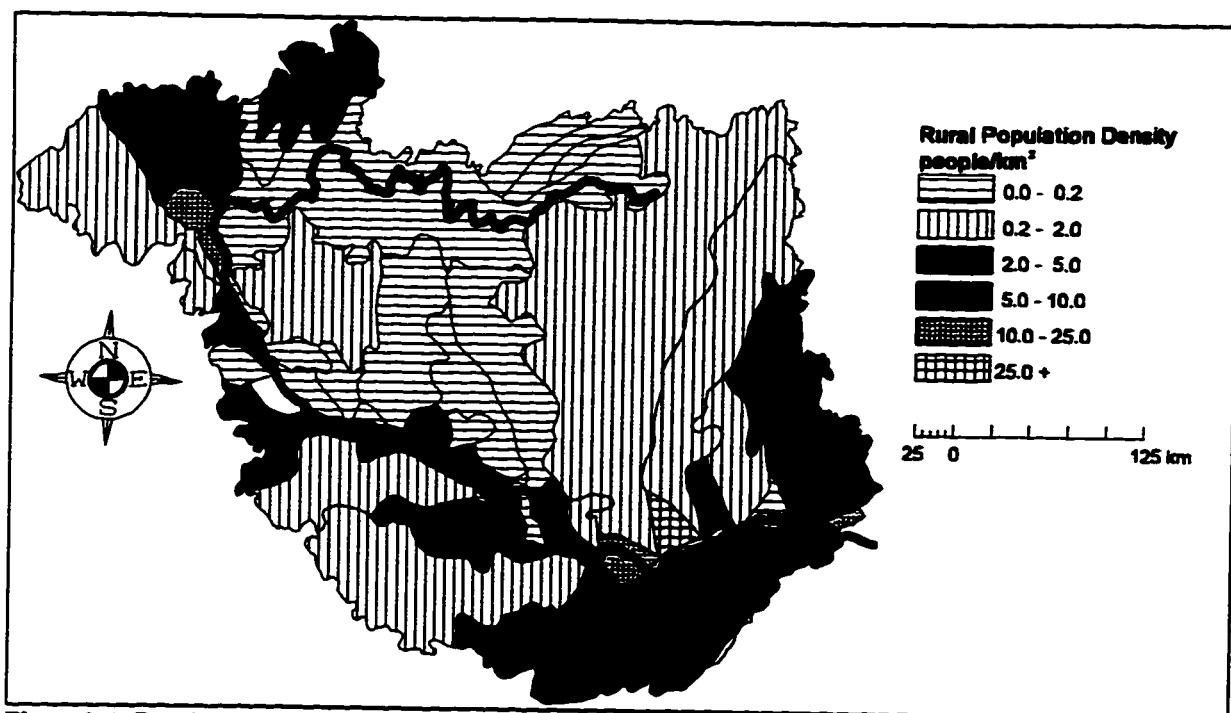


Figure 3-4: Rural population density.

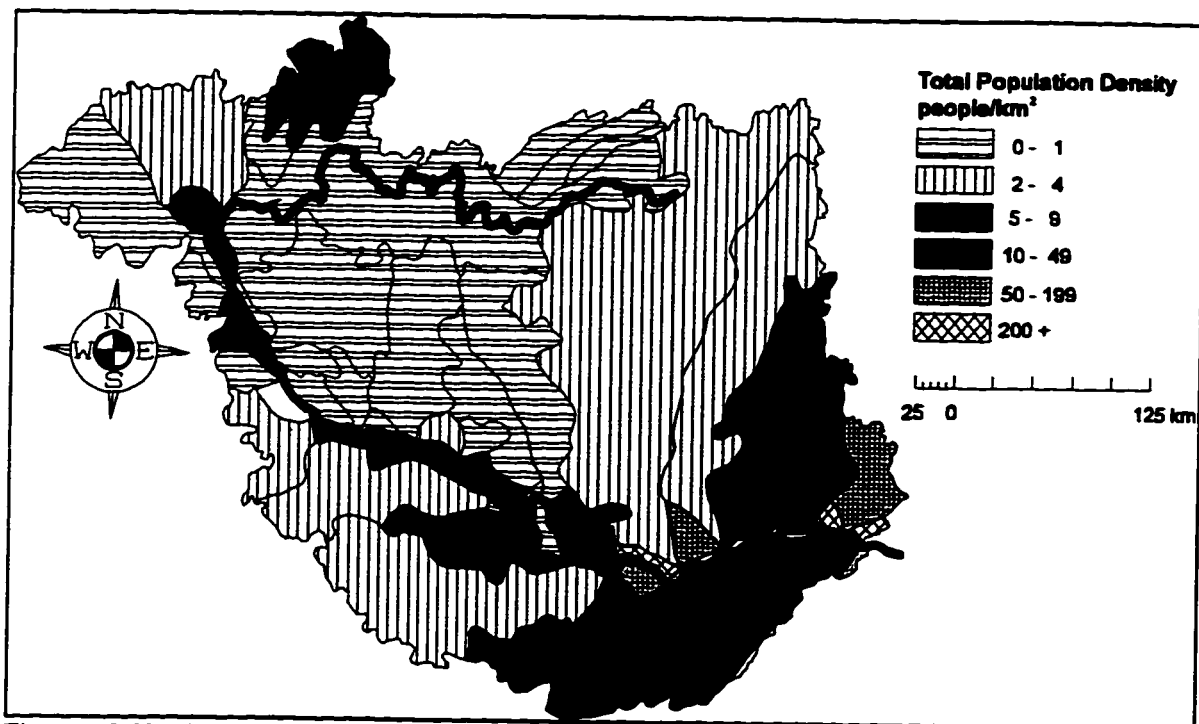


Figure 3-5: Total population density.

3.2.4 Hydroelectrical Installations

The size and distribution of hydroelectrical reservoirs and generating stations was obtained from the Ottawa River Regulation Planning Committee, Final Report (1980) and entered into the GIS database as points with attached attributes. Figure 3-6 illustrates the distribution and size of hydroelectrical reservoirs and generating stations in the basin.

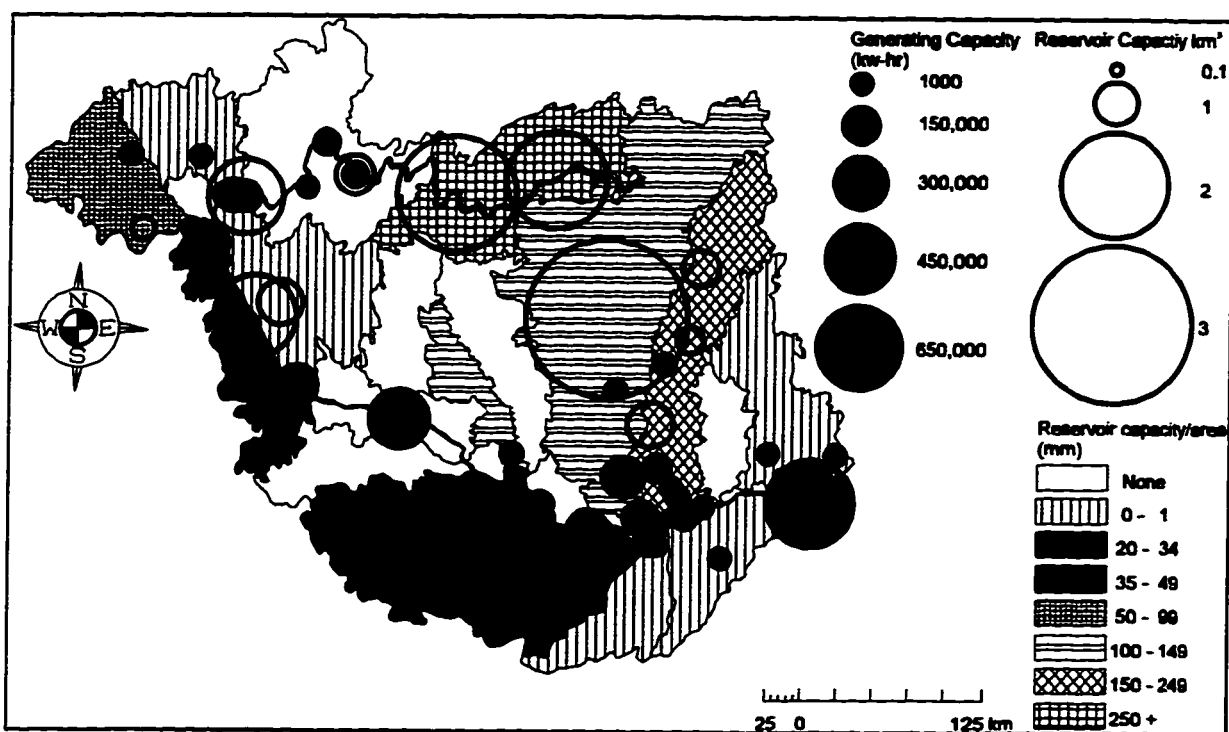


Figure 3-6: Reservoir and generating capacity for hydroelectrical installations and reservoir capacity per area for tributary basins expressed in mm (Data from Ottawa River Regulation Planning Committee, 1980).

3.3 EIS DATABASE

3.3.1 Land Cover

Land Cover was derived from Advanced Very High Resolution Radar (AVHRR) data by the Manitoba Centre for Remote Sensing (1993). Maximum resolution is 1km².

Environment Canada's EIS database is a repository for these data and the EIS manuscript

(Environment Canada, 1993) describes the nature of the data in more detail. Figure 3-7 illustrates the types of land cover found in the Ottawa River basin.

3.3.2 Dominant Tree Species

Dominant and subdominant tree species maps are available in digital format from Environment Canada (Environment Canada, 1993). For the purposes of this study, only dominant tree species were deemed necessary for analysis. Figure 3-8 is a map of the dominant tree species found in the Ottawa basin. Occhietti (1989) describes the recolonization of the land by forests after the Wisconsin glacialiation.

3.4 METEOROLOGICAL DATA

Daily meteorological data from 60 meteorological stations in or on the edges of the Ottawa River basin was acquired from the Atmospheric Environment Service, Environment Canada (1990). The data arrived as 60 files of 1 MB each in ASCII format. It was imported into Microsoft Access where it could be summarized as daily, monthly, or yearly means for any given year or years and output in a format suitable for import into the GIS. Within the GIS these data were contoured to produce monthly precipitation maps for the Ottawa basin. Further details on the nature of the data can be found in the Handbook on Climate Data Sources of the Atmospheric Environment Service (Phillips et al., 1988). Figure 3-9 contains these maps.

3.5 DIGITAL ELEVATION

Digital elevation was extracted from a global elevation file called ETOPO-5 which is maintained by the United States Geological Survey and has been enhanced by the Canadian Geodetic Survey. Figure 3-10 is a rendering of the elevation in the basin. Chapter 1 describes the major topographic features found in the basin in more detail.

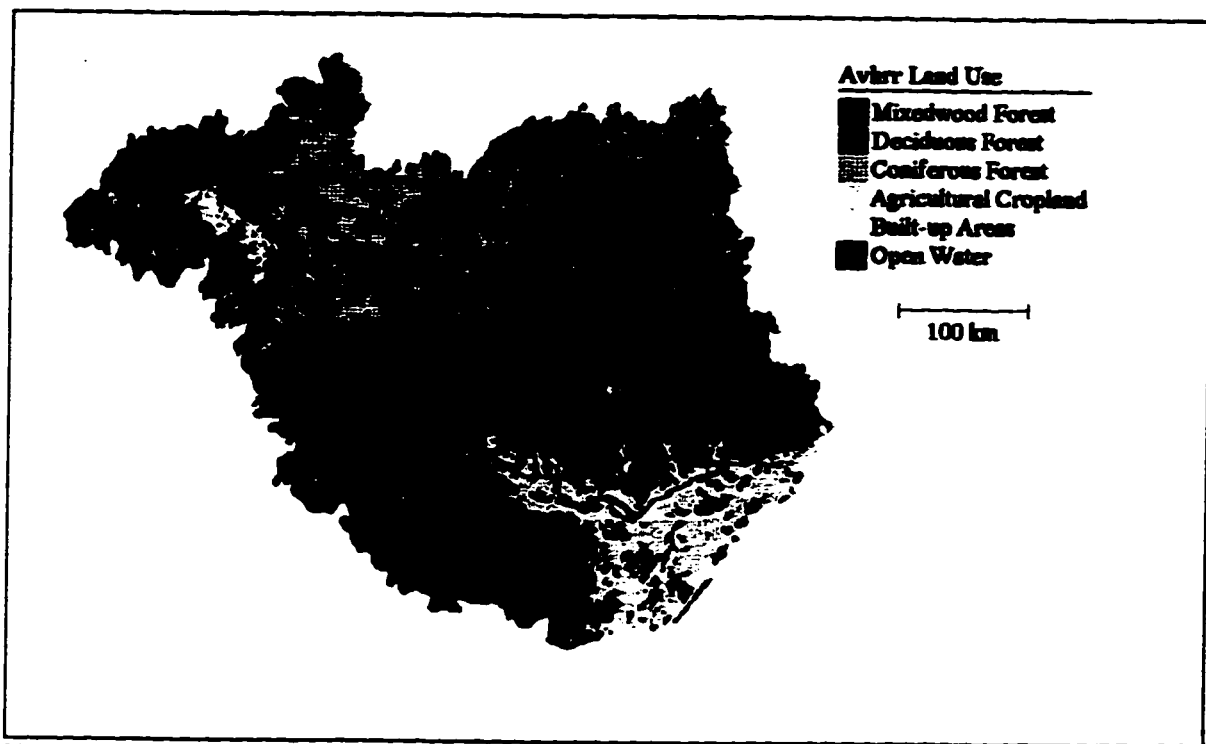


Figure 3-7: Land cover derived from AVHRR data (Manitoba Centre for Remote Sensing, 1993).

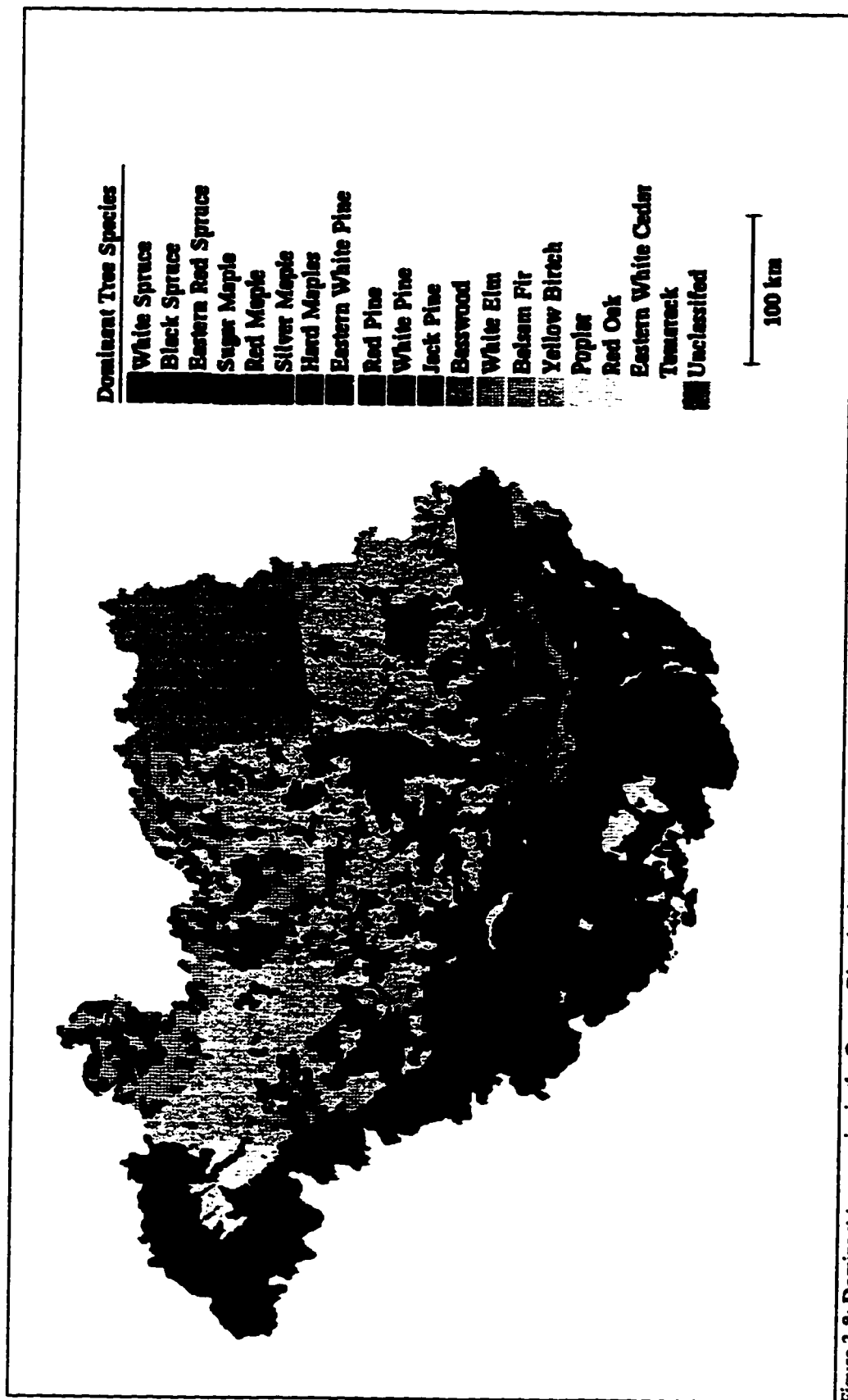


Figure 3-8: Dominant tree species in the Ottawa River basin (Environment Canada, 1993).

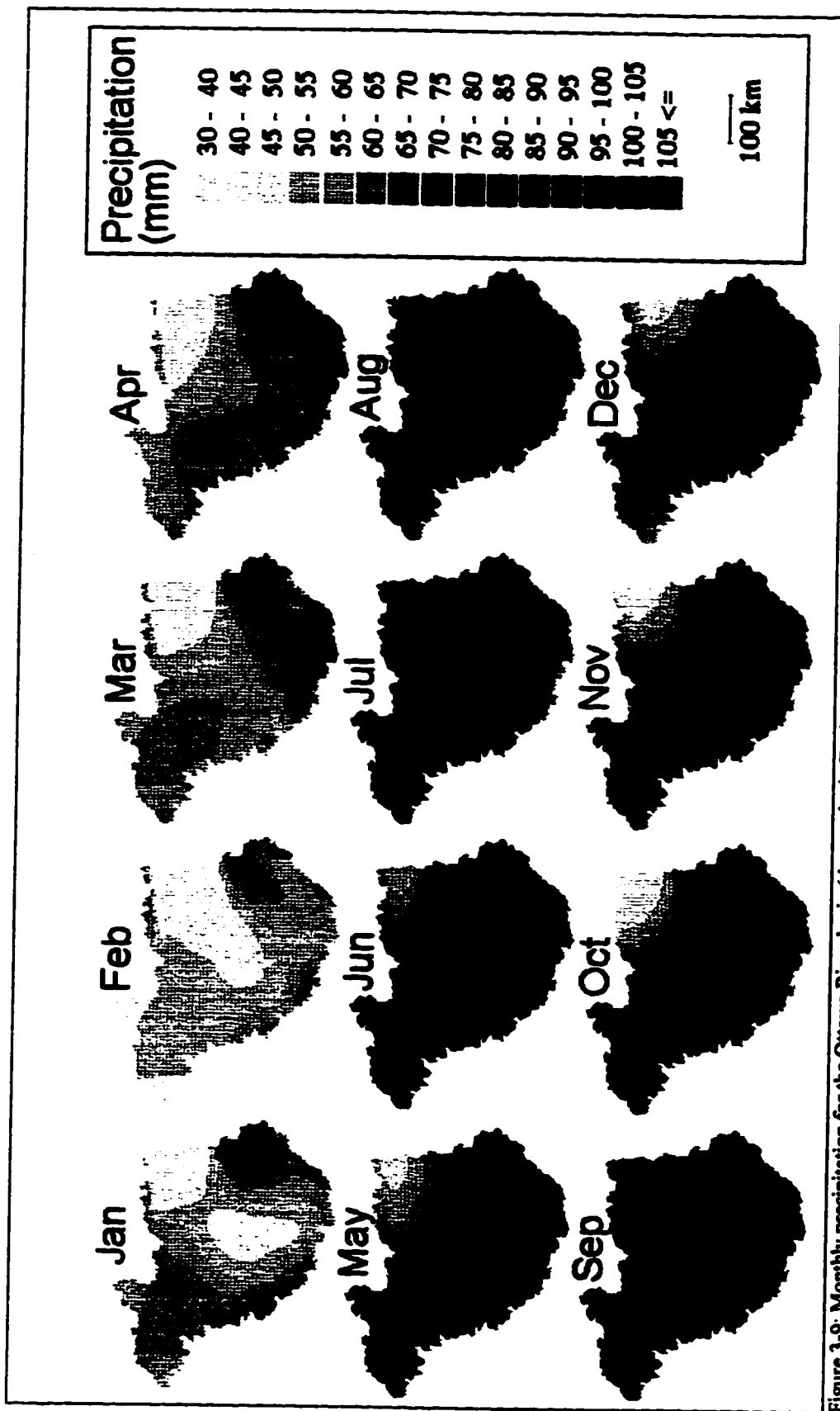


Figure 3-9: Monthly precipitation for the Ottawa River basin (Atmospheric Environment Services, 1990).

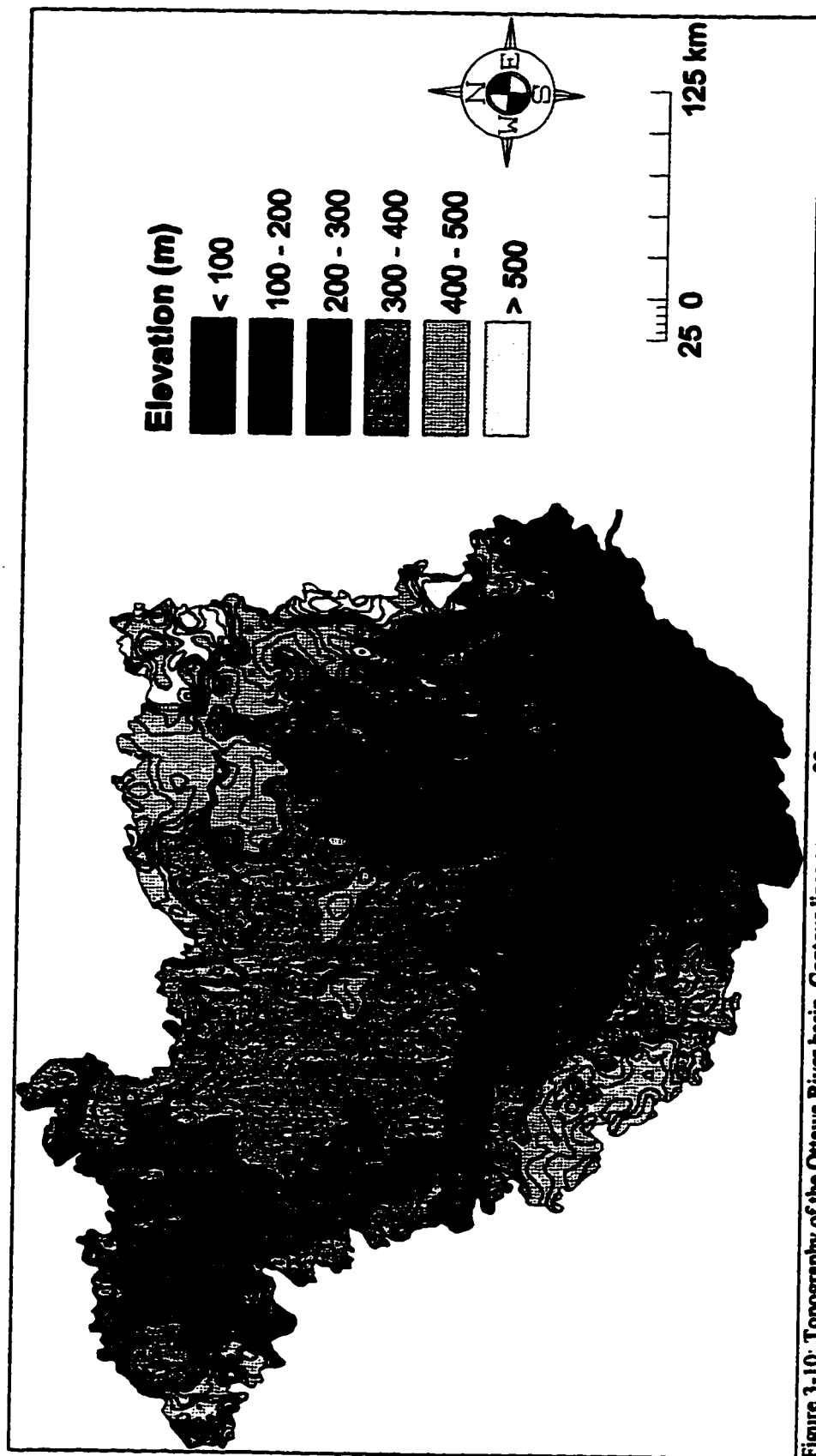


Figure 3-10: Topography of the Ottawa River basin. Contour lines are every 20 m.

3.5.1 Etopo5 and the Geodetic Survey DEM

This dataset contains worldwide bathymetric and elevation gridded data in meters with a 5 minute by 5 minute latitude/longitude data density. The data set was originally produced by the US Defense Mapping Agency. The National Geophysics Data Centre in Boulder Colorado produced the original data files. The Global Ecosystems Database Project (1986) of the National Geophysical Data Center is the repository for the data.

The Geodetic Survey at Energy Mines and Resources Canada has corrected and enhanced some parts of the Etopo5 dataset which lie in Canada. These enhanced data were used for this project (Véronneau, 1994). At this time, an estimation of accuracy for the Geodetic Survey enhanced dataset does not exist and therefore data accuracy for this project is assumed to be the same or better than that of the original Etopo5 dataset. The statistical nature of the data varies, depending on the source data set. Various sources include 5 and 10 minute data, point samples, averages and modal values. Data values are registered to even 5-minute boundaries. Registration errors of 10 minutes in both latitude and longitude are possible (Global Ecosystems Database Project, 1986).

3.5.2 Latitude Longitude Generation

In its primary form the Geodetic survey DEM exists only as a grid of elevation values ("z" values) without geographical coordinates (no x or y). It can be georeferenced if the geographical coordinates of one grid cell and the size of the grid (1 point every 5 arc minutes in this case) are known. Latitudes (x) and longitudes (y) for the Geodetic Survey DEM were generated in this manner by the latlon.exe program written by Véronneau (1994). This

program was modified to output negative integer longitudes to meet the import specifications of SPANS.

3.6 AREA CROSS TABULATION

Appendix B contains the percentage of various spatial entities of the Ottawa River basin, such as rock types per tributary drainage basin. This information was produced in SPANS by overlaying the map of the drainage basin boundaries with maps of the spatial entities using the area-crosstabulation command (TYDAC Technologies Inc., 1995a). These data will be referred to extensively throughout the subsequent chapters.

3.7 HISTORICAL WATER CHEMISTRY

The water quality branch at Environment Canada maintains a historical water quality database for all of Canada (Environment Canada, 1993). It has had several names, the most recent being "ENVIRODAT". The ENVIRODAT database is enormous, containing over 300 parameters measured by more than 1000 different techniques. The database is accessed by an awkward database management system (DBMS) on a mainframe computer. The level of complexity of ENVIRODAT combined with the limited DBMS system makes working with the database difficult and renders some operations impossible. To alleviate this problem, all possible records for the Ottawa River basin were extracted to a flat ASCII file, 42 MB in size. This file was imported into Microsoft Access where useful data were then selected and summarized for the purposes of this thesis.

A total of 324,262 records lie in the Ottawa River basin, the first was recorded in 1947. Initially, 2 criteria were used to reduce the dataset to a manageable size: (1) only the

same parameters as those measured in the field were extracted; (2) only station localities similar to those of the field work were extracted - such as the major tributaries and the Ottawa River stations. These criteria reduced the dataset to 82,016 records. To further reduce the dataset, the temporal distribution of the measured variables, the total count of measurements, and the method used in the analysis of the given parameter were used as filters for selection. This reduced the dataset to 60,841 records. Details on the analytical methods used to collect data for the ENVIRODAT database can be found in the NAQUADAT/ENVIRODAT Dictionary of Codes (Environment Canada, 1991). Table 3-1 lists all localities used in this study as well as calculated monthly mean alkalinity measurements and some calculated summary statistics as an example of the data. To present a more detailed summary of the database, monthly averages and summary statistics were calculated for all parameters and all localities used. These can be found in appendix C. Table 3-2 lists the parameters that were extracted from the database.

Station	Lat	Long	Station No.	Var	Std	Cnt	Max	Min	Avg	First	Last	Monthly Means											
												Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ottawa River Stations																							
At Otto Holden G.S.	46.378	78.728	On02Je0004	13	4	55	24.2	2.0	16.8	1971	1984	10.0	14.4	14.8	15.1	13.8	16.2	17.3	19.5	19.5	18.7	19.9	17.7
At Chata Falls G.S.	45.475	76.239	On02Kf0011	71	8	43	48.0	5.0	29.4	1971	1984	29.8	34.8	37.6		34.2	26.4	21.1	20.5	18.5	26.3	35.9	30.8
At Hawkesbury	45.618	74.600	On02Lb0002	62	8	33	44.0	0.1	22.8	1970	1984	21.3	21.1		13.7	27.9	25.1	19.8	19.9	20.0	26.1	22.6	25.1
Au Pont, Route 101	47.589	79.485	Pq02Jc0001	5	2	108	22.0	3.0	6.5	1976	1988	5.7	6.5	7.2	6.1	7.4	6.6	6.9	6.8	6.6	5.9	6.4	6.0
Au Pont, Temiscaming	46.712	73.101	Pq02Je0003	8	3	114	22.0	6.0	16.2	1978	1988	16.6	14.8	14.5	12.4	13.5	17.1	18.5	18.5	18.3	16.9	16.7	17.7
Au Barrage Cheneaux	45.584	76.675	Pq02Kc0002	10	3	116	36.0	7.0	14.0	1978	1988	15.6	16.1	16.0	13.6	12.8	12.0	13.0	14.4	13.0	13.3	13.2	14.3
A la Traversée de Mason	45.523	75.411	Pq02La0002	49	7	97	46.0	9.0	22.3	1980	1988	20.3	22.3	22.8	28.0	24.8	21.4	17.3	18.3	19.7	22.8	20.4	34.8
Au Barrage de Carleton	45.568	74.384	Pq02Lb0002	48	7	160	43.0	5.0	23.9	1978	1988	22.3	22.1	23.7	29.0	22.7	20.8	21.5	20.5	20.0	27.1	26.2	30.1
Tributary Stations																							
Mattawa River	46.319	78.708	On02Je0014	11	3	38	22.5	9.1	15.3	1971	1984	17.0		16.1	12.5	11.3	14.0	17.7	15.9	19.0	15.6	16.9	14.8
Pelawawa River	45.888	77.308	On02Kb0001	783	28	97	241.2	6.1	18.1	1970	1984	23.2	12.7	16.2	11.8	10.5	11.3	14.0	12.6	14.2	19.7	58.6	18.9
Bonnechere River	45.497	76.564	On02Kc0001	259	16	104	116.0	13.0	66.7	1970	1984	70.1	66.7	65.0	64.6	66.0	72.6	56.6	59.8	51.9	75.6	81.1	75.0
Madawaska River	45.433	76.350	On02Kd0002	342	18	116	216.0	4.0	44.0	1971	1984	41.1	41.0	34.5	45.3	42.5	42.8	44.3	66.6	42.4	46.3	44.5	39.3
Mississippi River	45.423	76.253	On02Kf0002	265	17	89	117.0	7.0	93.2	1970	1984	102	100	86	86	84	97	94	97	80	103	96	98
Rideau River	45.416	75.683	On02La0002	743	27	114	205.0	21.0	129.1	1970	1984	160	159	127	111	134	135	122	105	113	125	140	140
South Nation River	45.559	75.064	On02Lb0009	1921	44	105	241.9	13.9	146.2	1970	1984	161	147	125	126	155	137	153	144	113	161	176	173
Rivière Kipewa	47.042	79.271	Pq02Je0002	3	2	61	14.0	0.9	2.9	1978	1988	2.0	4.1	2.8	3.2	2.4	3.0	2.8	3.0	3.4	2.5	2.5	3.2
Rivière Coulonge	45.651	76.730	Pq02Kd0002	135	12	81	88.1	2.5	10.3	1979	1988	9.1	16.2	14.5	5.1	4.8	7.6	10.4	11.0	25.2	6.0	6.2	6.5
Rivière Du Nord	45.563	74.338	Pq02Lc0002	129	11	81	84.0	3.0	27.1	1978	1988	29.8	36.7	28.0	14.8	26.1	23.3	26.8	30.1	27.4	26.4	26.9	19.4
Rivière Rouge	45.643	74.691	Pq02Lc0013	24	5	114	40.0	4.2	11.6	1976	1987	11.4	15.2	13.3	6.7	7.2	10.9	14.9	12.8	12.9	9.9	10.3	16.5
Rivière Petite Nation	45.605	75.126	Pq02Ld0001	129	11	87	96.0	0.0	24.0	1971	1988	32.8	21.7	27.2	21.3	16.3	19.7	22.7	25.3	25.1	29.1	22.5	21.3
Rivière Du Lièvre	45.586	75.419	Pq02Lf0004	6	3	76	21.0	2.9	14.4	1976	1988	12.6	14.3	15.0	16.3	13.9	14.0	16.1	12.7	14.3	14.9	14.0	15.7
Rivière Gatineau	45.487	75.749	Pq02Lh0004	15	4	165	25.0	1.4	12.4	1976	1988	10.6	9.8	11.5	17.9	17.0	11.0	12.1	12.0	11.4	11.9	10.9	12.6

Table 3-1: Monthly mean alkalinity (total CaCO₃ mg/l) and calculated statistics of the Ottawa River and its major tributaries (calculated from Environment Canada, 1993).

Table 3-1: Monthly mean alkalinity (total CaCO₃, mg/l) and calculated statistics of the Ottawa River and its major tributaries (calculated from Environment Canada, 1993).

No.	Parameter
1	Alkalinity Total CaCO_3
2	Aluminum Extractable
3	Ammonia Dissolved
4	Ammonia Total
5	Calcium Total
6	Carbon Dissolved Inorganic
7	Carbon Dissolved Organic
8	Carbon Total
9	Carbon Total Inorganic
10	Chloride Dissolved
11	Iron Extractable
12	Iron Total
13	Magnesium Total
14	Manganese Extractable
15	Manganese Total
16	Nitrogen Dissolved
17	Nitrogen Dissolved Kjeldahl
18	Nitrogen Dissolved NO_3 & NO_2
19	Nitrogen Total Kjeldahl
20	Oxygen Dissolved
21	pH
22	Phosphate Dissolved
23	Phosphorus Suspended Particulate
24	Phosphorus Total
25	Phosphorus Total Dissolved
26	Potassium Dissolved
27	Silica Reactive
28	Sodium Dissolved
29	Specific Conductivity
30	Strontium Total
31	Sulphate Dissolved
32	Temperature Water

Table 3-2: Parameters extracted from the ENVIRODAT database (Environment Canada, 1993).

3.8 HYDROMETRIC DATA

Discharge data for the Ottawa basin were obtained from the HYDAT database maintained by the Surveys and Information Systems Branch at Environment Canada but recently taken over by the Atmospheric Environment Service and distributed by Greenland Engineering Group (Atmospheric Environment Service, 1994). Many problems similar to those encountered with the aforementioned ENVIRODAT database were also evident here: (1) the number of stations which lie in the Ottawa River basin is large; (2) the methods used to measure discharge are diverse; (3) some records are not continuous; (4) the data can be

extracted in many forms such as monthly averages, daily averages, or daily extremes; (5) the format of the output is difficult to work with - ASCII format for daily averages.

To facilitate the needs of the study and make the dataset manageable, only stations that met the following criteria were used: (1) flow in m^3/s was measured with a meter; (2) the dataset is large (greater than 15 years) and continuous during the last 15 years; (3) the data continue up to 1992; (4) the data represent the entire flow of the river at that point in its course and not a partial flow; (5) for tributaries, stations as close to their mouth as possible were chosen. Table 3-3 lists the stations selected using these criteria, their annual discharge and gross drainage area, and some summary statistics calculated from the data.

The extraction software which accompanies the HYDAT database also calculates some basic statistics such as mean annual discharge. However, it was discovered that the method utilized by the extraction software is based on mean monthly discharges and not on the actual raw data. This method does not account for the different number of days in a month (mean February discharge is weighted the same as mean April discharge). Since February discharge is typically very low, discharge is slightly underestimated. For example, the extraction software calculates mean annual discharge at the mouth of the Ottawa River to be $1928 \text{ m}^3/\text{s}$ when its true value is $1934 \text{ m}^3/\text{s}$. The degree of this error depends on the distribution of discharge throughout the year. To eliminate these errors, statistics from the extraction software were not used.

Station Name	Station no.	Province	Latitude	Longitude	First Year	Count	Daily Max.	Daily Min.	Daily Std.	Month Max.	Month Min.	Month Std.	CV	Gross Drainage Area	Mean Discharge m ³ /s
Main River															
Au Reservoir Dozois	02JA003	PQ	47.6128	77.3072	1965	6574	513	2	82	342	0	77.9	0.53	8210	155
Au Lac Granet	02JB009	PQ	47.8442	77.5500	1977	5840	568	38	80	433	35	77.5	0.42	10300	189
Au Barrage de Rapide-Sept	02JB005	PQ	47.7683	78.3108	1939	19236	1240	8	97	1100	44.7	84.4	0.47	13100	208
Au Lac Simard	02JB006	PQ	47.9333	78.5772	1954	13698	782	18	83	613	87.6	70.1	0.38	14000	219
Barrage des Rapides des Quinze	02JB008	PQ	47.5914	79.2950	1965	9589	1280	39	130	832	141	111	0.37	23400	351
At La Caver Rapids (Mattawa)	02JE012	ON	46.3778	78.7233	1952	15325	3650	2	324	2800	227	289	0.47	47800	692
At des Joachims (Robitton)	02KA002	ON	46.1833	77.6978	1950	15885	4800	92	387	3080	287	331	0.49	57500	810
At Chata Falls	02KF009	ON	45.4750	78.2382	1915	28765	5800	288	685	4670	334	688	0.58	89600	1144
Au Barrage de Carleton	02LB024	PQ	45.5700	74.3928	1982	10807	8190	308	1027	6500	770	903	0.53	143000	1933
Tributaries															
Kinojivis	02JB013	PQ	48.3842	78.8581	1965	9454	452	7.8	40.2	171	8.11	33.8	1.01	2590	39.9
Blanche	02JC008	ON	47.8892	78.8792	1968	9192	280	1.9	30.1	121	3.18	23.9	1.32	1780	22.7
Montreal River	02JD010	ON	47.1375	78.4542	1972	8036	589	0.2	70.0	407	10.4	53.6	0.86	6600	81.1
Mattawa	02JE020	ON	46.2989	78.9072	1971	8093	176	0.7	16.6	68.5	1.78	12.8	1.07	909	15.5
Dumoine	02KJ004	PQ	46.3458	77.8158	1965	10209	352	12	49.8	211	9.21	37.2	0.83	3780	60.3
Petawawa	02KB001	ON	45.8881	77.3083	1915	28507	467	4.5	48.1	247	5.31	42.3	1.02	4120	48.3
Coulange	02KG001	PQ	45.8739	78.8858	1928	24094	808	6.2	76.6	410	9.58	65.9	1.02	5150	75.0
Bonnechere	02KC009	ON	45.4889	78.5639	1921	25755	286	0.3	21.9	123	2.39	19.3	1.11	2380	19.7
Madawaska	02KE005	ON	45.4089	78.5078	1949	18432	565	0.3	79.3	438	6.73	66.6	0.85	8180	93.0
Mississippi	02KF008	ON	45.1767	78.1242	1918	27486	260	3.5	32.9	181	4.98	30.8	1.08	2900	30.6
Rideau	02LA004	ON	45.3817	75.6978	1933	20102	583	1.5	59.2	308	3.55	45.8	1.52	3830	39.1
Gatineau	02LH009	PQ	45.8094	75.9319	1964	10136	2240	46	137.7	1200	140	118	0.39	22500	350.6
Lievre	02LE024	PQ	46.7842	75.3139	1979	5233	484	42	75.9	298	24.7	42.9	0.46	4530	163.6
Petite Nation	02LD005	PQ	45.7917	75.0914	1968	9036	140	2.3	22.0	103	2.71	19.8	0.98	1330	22.5
South Nation	02LB005	ON	45.5084	74.9558	1915	26200	1190	0.3	99.8	461	0	72.3	2.39	3810	41.8
Rouge	02LC029	PQ	45.7384	74.6897	1984	10437	765	10	98.8	488	16.3	81.6	0.96	5480	104.6
Nord	02LC008	PQ	45.7931	74.0128	1930	23090	380	2	39.5	150	4.13	23.1	1.07	1170	38.9

Table 3-3: Discharge in m³/s and calculated statistics for selected stations along the Ottawa River and its major tributaries (calculated from Atmospheric Environment Service, 1994). ¹CV = Coefficient of Variation.

3.9 CHEMICAL ANALYSIS

The collection and analyses of water samples in the field and laboratory is described in the previous chapter. In order to link these data to the GIS database, the geographical coordinates of the sampling stations were determined from 1:50,000 scale NTS topographic maps. The entire table of analyses was then imported into the SPANS study area for subsequent analyses.

4 WATER BALANCE

The variations in many characteristics of rivers, such as the dissolved and suspended loads, are strongly controlled by the water balance of the basin and its variations. For example, evaporative losses cause elemental concentrations to increase and fluctuations in the chemistry of rivers are almost always associated with fluctuations in discharge. A preliminary understanding of the water balance of a river basin is therefore essential for interpreting other river characteristics.

Understanding the water balance of a hydrologic basin is not an easy task. Initially, researchers tried to determine some water balance rules which could be applied universally to all catchments. Many intra-basin studies were conducted under the precept that the underlying controls on waterflow were the same for each basin. As knowledge in the field grew, it was realized that few of these comparisons were fruitful and that often the nature of flow in a single basin is complex and can be unique. In the past ten years there has been growing recognition that more emphasis must be placed on the physical characteristics of basins in hydrological models. McCullough and Robinson (1993) stress the need for development of physically based models. Kachroo (1992) points out the advantages of this type of approach over traditional empirical discharge models based only on historical records of discharge. Bonell (1993) summarizes the present state of such models. Two main aspects of the water balance of the Ottawa River basin are looked at here: (1) the nature of discharge throughout the basin and its relation to physical basinal characteristics such as geology and vegetation; (2) calculations of, and relationships between, precipitation, runoff, evapotranspiration, evaporation, and transpiration.

The analysis described next is based on meteorological (Atmospheric Environment Services, 1990) and hydrometric data (Atmospheric Environment Service, 1994) current until the end of 1992 and on isotopic data collected and analyzed during this project. These datasets are discussed in chapters 2 and 3.

4.1 HYDROGRAPHY

The recording of hydrographic data became commonplace shortly after the turn of the century and an extensive network of hydrographic monitoring stations now exists in many parts of the world. Since the collection of these data began, hydrological records have been analyzed with a battery of statistical techniques, almost exclusively for the purposes of designing and operating water resource projects. Initially, researchers tried to determine periodicity in stream flow and precipitation for purposes of prediction, but it was soon realized that natural hydrologic processes are not entirely deterministic, rather they result from a combination of deterministic and stochastic behaviour (Yevjevich, 1972). In other words, discharge from rivers is both periodic and governed by the laws of chance. Following this realization, many attempts have been made to model the stochastic nature of rivers. An excellent review of these models can be found in El-Shaarawi and Esterby (1982) and later in Beard et al. (1992). Most of the effort has focused on the nature of unregulated discharge and few studies (if any) were carried out for the purposes of interpreting the chemical variations in river water. However, the disruption in the natural flow of rivers that alters many discharge-dependent variables has prompted studies on the degree and nature of flow regulation, such as those by Cassidy (1990), Malik and Podol'skaya (1979), Jiongxin (1990), and Jourdonnais and Hauer (1993). Their analyses are primarily based on the visual interpretation of hydrographs

and on standard statistical parameters. Others (Bundi et al., 1990; Chambers et al., 1991; Morgan et al., 1991; Newson, 1994) have focused on the timing of peak discharge events and the spatial variation in land-surface moisture regimes as a method to understand the adverse impacts of flow regulation on ecosystem health.

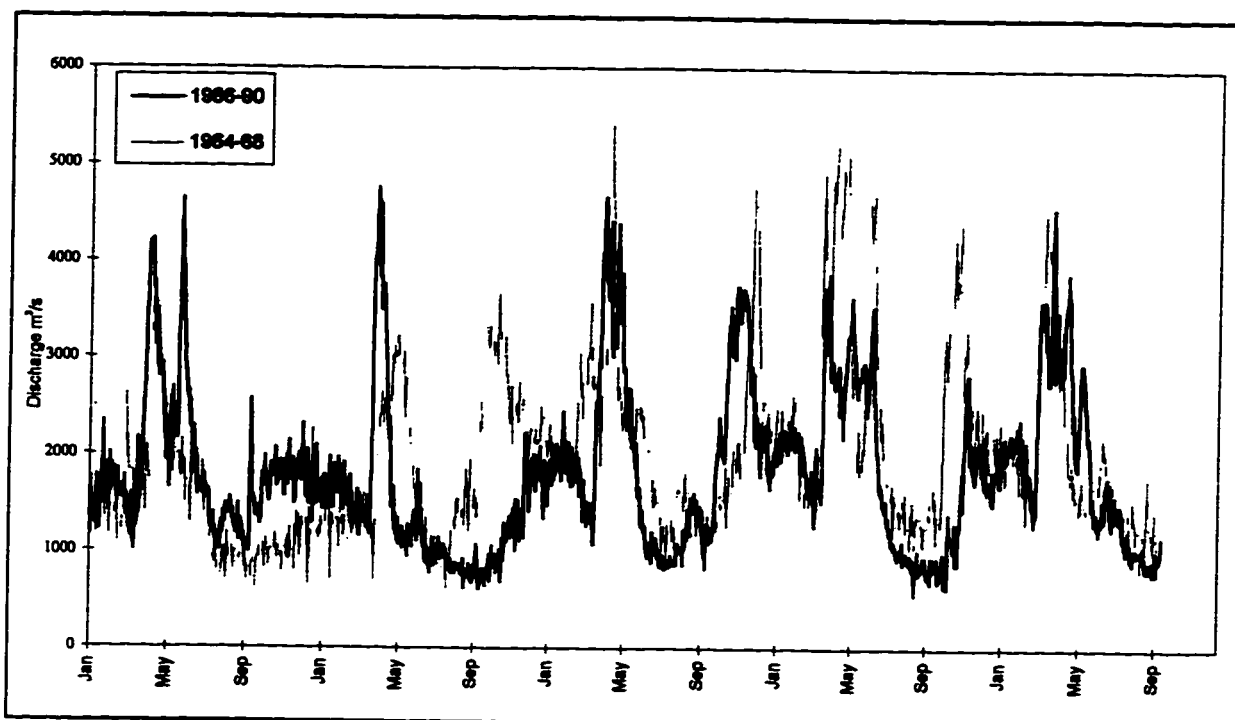


Figure 4-1: Mean daily discharge of the Ottawa River at Carrillon Station, 1964-68 & 1986-90.

In order to understand the timing of chemical inputs to the Ottawa River, time series analyses (autocorrelation and crosscorrelation) of discharge was done for various gauging stations along the river and for the major tributaries. These techniques have been marginally utilized in hydrological analyses previously, primarily by those attempting to model the stochastic nature of discharge. For example, Rao and Quillan (1982) autocorrelated discharge from the Chattahoochee River in Georgia as part of a procedure for building a model intended to predict future flows. Siegerstetter and Wahli (1982) crosscorrelated simulated time-series of gauging stations on the Danube River as part of a procedure to optimize the

operating strategy of the water works on that river. Kottegoda (1982) investigated non-stationary behavior in hydrology by using autocorrelation in modeling the relationship between precipitation and discharge in northern Utah and in Egypt. Finally, Hipel et al. (1982), Camacho et al. (1987) and Thompstone et al. (1987) crosscorrelated precipitation, temperature and discharge in order to identify possible transfer functions between them. The results of these analyses were intended as guides for prediction of future discharge events. Attempts to characterize flow within a river basin by these techniques for purposes of interpreting temporal chemical fluxes seem to be unknown in the literature.

4.1.1 History and Degree of Regulation

The Ottawa River basin is one of the most highly regulated catchments in Canada. The use of the river for hydro-electric power generation and to a lesser degree for navigation has led to the development of a total reservoir storage capacity of 13.9 km^3 (calculated from Ottawa River Regulation Planning Committee, 1980) or 23% of the total runoff. Flood control and flow augmentation result from the operation of these reservoirs to store water during spring runoff for release at later times of low natural flow, primarily the late summer and winter. The major reservoirs are near the headwaters of the river and thus flow moderation is less effective in its lower reaches where the unregulated tributary discharge is large. The flow at the mouth of the river, therefore, resembles its pre-historical state but, as will be seen, other portions of the basin suffer drastic alterations in their natural flow regime. During low flow periods, long-term mean monthly flows have been augmented by roughly 30% in the summer months and as high as 60% in the winter months at the Temiskaming dam at the foot of Lake Temiskaming. These effects are considerably less in lower reaches of the

river. The location, size, and date of emplacement of hydro-electrical installations in the Ottawa basin is summarized in figure 3-6, chapter 3.

4.1.2 Characteristics of flow at the mouth of the river

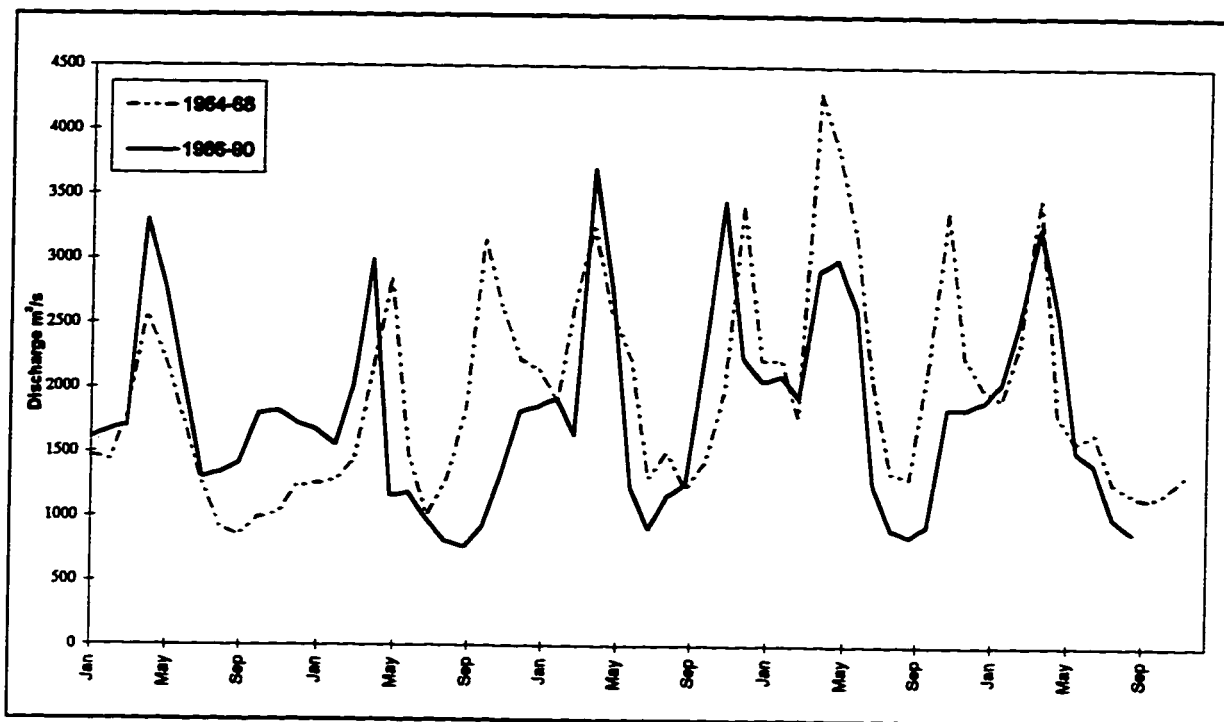


Figure 4-2: Mean daily discharge averaged monthly of the Ottawa River at Carillon, 1964-68 & 1986-90.

Figure 4-1 and Figure 4-2 plot the discharge at the mouth of the Ottawa River at daily and monthly time scales, respectively. Some observations can be made by visual inspection of the hydrographs. Daily discharge is characterized by sharp peaks and exponential decay. It is a noisy signal indicating that the cause-effect relationship between runoff and climate is stronger in the short term (Unny, 1982). Clearly, the two series, 1964-68 and 1986-90, differ substantially, the size and timing of peaks and troughs in both series varying in accord with the stochastic nature of discharge over both long and short terms. However, deterministic periodic signals are also evident, represented by the dominant high water stand of the spring thaw, low water stand during the late summer, a more variable and less dominant fall high

water period, and generally stable or slightly decreasing flow throughout the winter. The stability of the flow throughout the winter is the result of flow augmentation practices by hydro-electrical reservoir operators (Ontario Hydro, 1991). This is also true of a portion of the summer flow, but to a lesser degree. During prehistoric times, the hydrograph would have had the same general shape but with greater amplitude and variation - higher highs and lower lows - looking much as the unregulated tributary hydrographs which are discussed later. Another semi-periodic feature worth noting is the occasional mid-winter thaw represented by sharp peaks and a general rise in discharge typically sometime in January. All of these cycles, even the mid-winter thaw, appear to have a minimum period of one year.

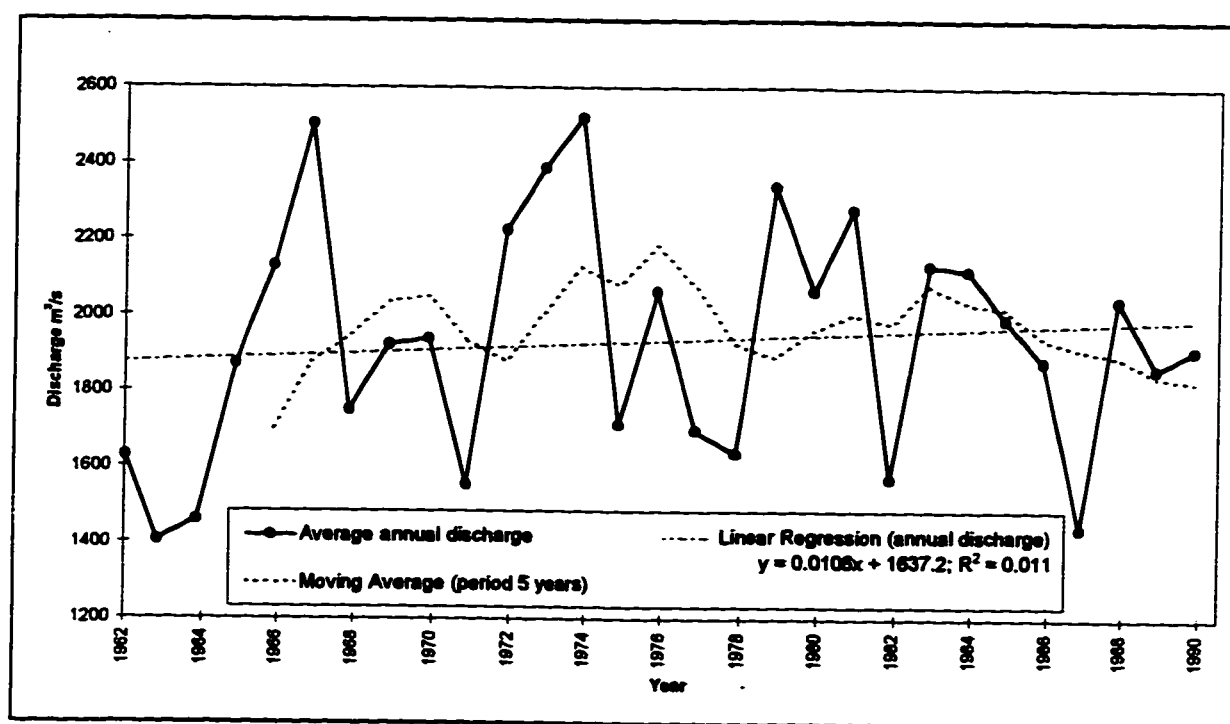


Figure 4-3: Yearly mean discharge of the Ottawa River at Carillon 1962-90.

The long term discharge record shown in Figure 4-3 is in stark contrast to the annual cycles shown in Figure 4-1 and Figure 4-2. It appears to fluctuate randomly between values of roughly 1400 and 2500 m³/s. However, Unny (1982) describes the existence of groups in

yearly discharge records corresponding to spells of flood and drought years and suggests that this “persistence” indicates that the signal is not purely random. Richey et al. (1989) believe this to be the case for the Amazon River. Using spectral analyses of long term discharge records for the Amazon River, they have detected 2-3 year cycles that they believe to have been related to fluctuations in the surface water temperature of the Pacific Ocean known as El-Niño cycles. The mildly increasing trend in average discharge over the last 28 years for the Ottawa River, shown by the line of linear regression and to a lesser degree by the 5 year moving average, is not statistically significant and may be due entirely to chance. However, as noted by many other researchers (Saxton and Shiau, 1990; Bren, 1993; McCullough and Robinson, 1993; Bosch and Hewlett, 1982), such a trend may also be due to changes in land use, such as deforestation and/or urban growth. Other researchers have used these trends as evidence of climatic change. Burn (1994) looked at the timing of spring runoff in 84 natural rivers in Canada and concluded that there are a greater number of rivers that exhibit earlier spring runoff than can be attributed to chance, possibly due to greenhouse-gas-induced climatic change. Probst and Tardy (1987) calculated a 3% increase in global river flux since 1900, possibly due to climatic and/or land use changes. The relatively unnatural state of the Ottawa River and its tributaries render it a poor choice for analysis of this type.

4.1.3 Flow Variability Along the River

Figure 4-4 shows the average annual behavior of flow for gauging stations along the length of the river, essentially from its headwaters to its mouth. The log scale dampens the seasonal signal but was necessary in order to compare the lower discharges in the headwaters with those further downstream. An immediately striking feature of the plot are the inverse

trends in the headwaters and in downstream portions of the river. This is the result of flow regulation practices, where water is stored during spring thaw for release during later periods of low natural flow to maintain a sufficient supply of water for the generation of electricity throughout the year. As a result, the flows from the headwater areas are directly out of phase with nature. Points downstream receive progressively greater portions of unregulated water, ultimately giving the river a relatively natural signal at its mouth.

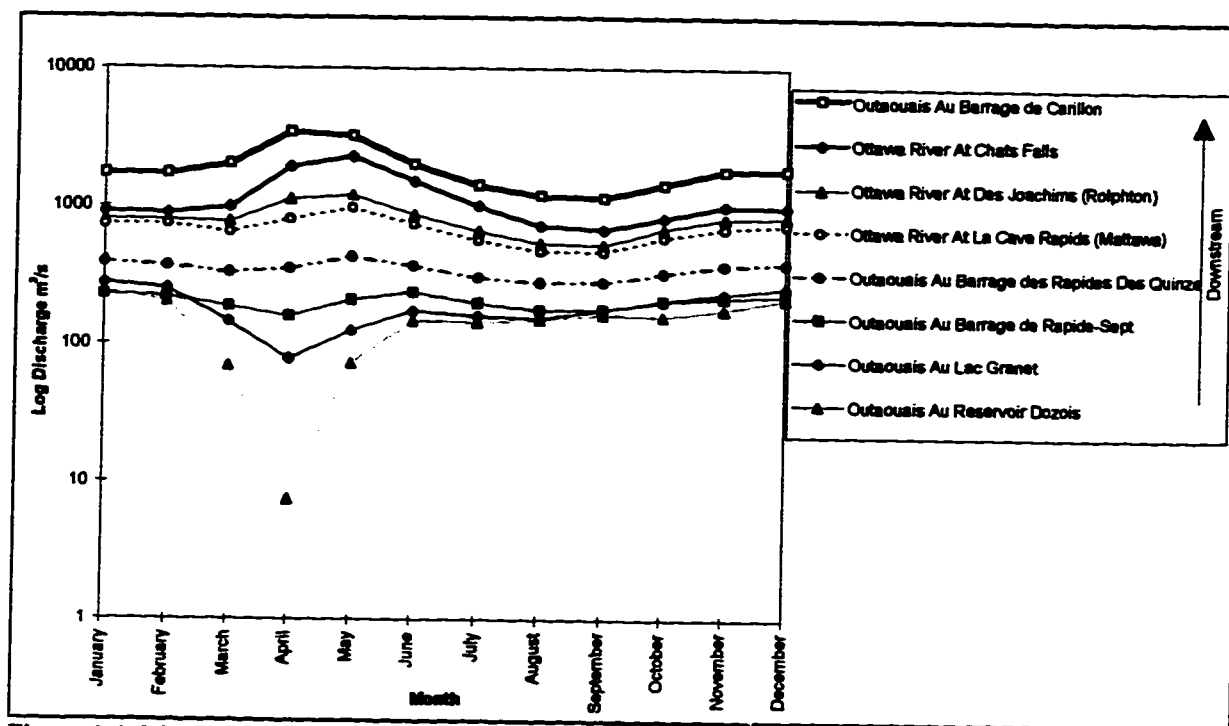


Figure 4-4: Mean monthly discharge for stations along the length of the Ottawa River.

4.1.4 The Flows of Tributaries

Hydrographs of tributaries have the same general trend as that of the mouth of the Ottawa River but with different amplitude and persistence of events (Figure 4-5). With the exception of the Rivière Gatineau, the tributaries shown are relatively unregulated, that is they contain no large unnatural reservoirs, and as such they represent more accurately the state of natural flow in the basin than does the Ottawa River. For most of the unregulated tributaries

there are two low water-stands, one in the summer and another lower one in the winter. Generally the winter low is 20% lower than the summer one (this is not the case for the Ottawa River, even at its generally unregulated mouth, where flow augmentation practices keep winter flows above those of the late summer). Low flows in the summer are caused by large water losses to the atmosphere by evapotranspiration whereas those in the winter are the result of seasonal groundwater drawdown. This will be discussed further later in the chapter.

Table 3-3, chapter 3, contains a statistical summary of discharges for the major tributaries as well as for the Ottawa River gauging stations. A useful statistic for describing the temporal variation of flow is the coefficient of variation (CV). This parameter, which is equal to the standard deviation divided by the mean, ranges from 0, for no variation, to numbers greater than 1, for extreme variation. A quick perusal of table 3-3 reveals that the CVs for tributaries are typically slightly greater than 1 indicating a strong degree of variation in their annual flows and they are greater than the CVs for the Ottawa River stations which typically have values of ~0.5. There are reasons for and exceptions to these trends.

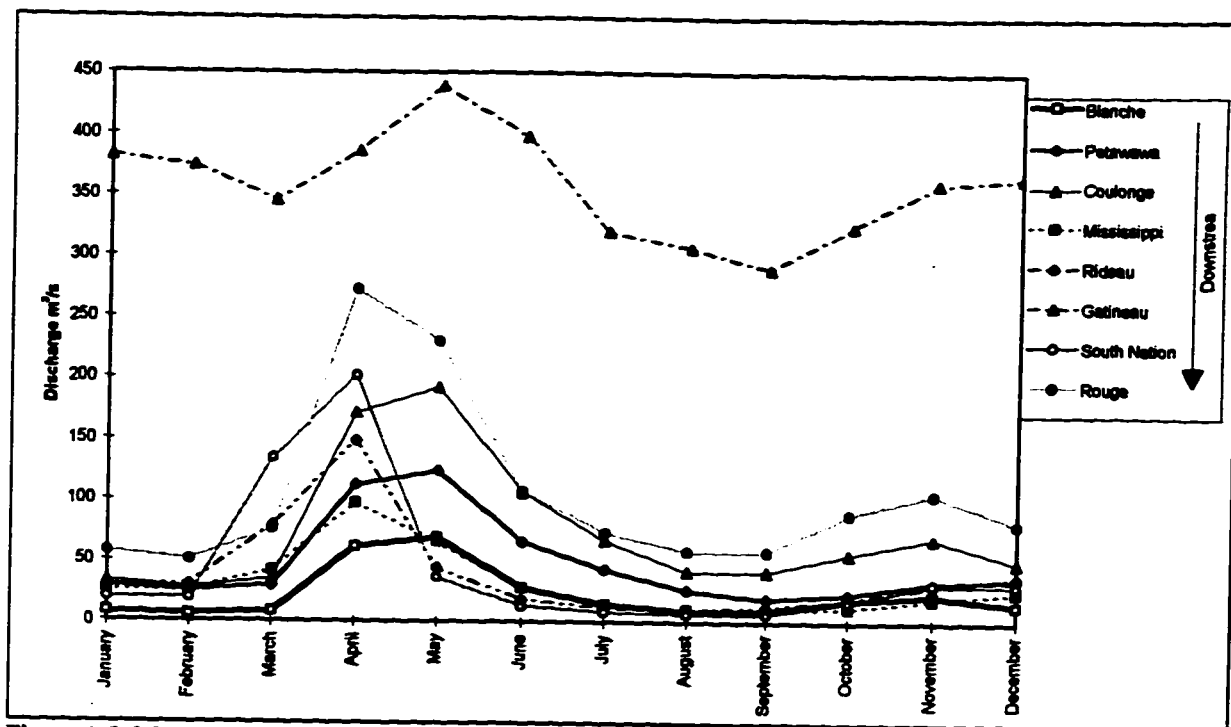


Figure 4-5: Mean monthly discharge of selected tributaries of the Ottawa River.

In general, under geologically homogenous conditions, the variability of runoff is proportional to the hydraulic gradient (basin slope for large areas) and inversely proportional to the size and total precipitation of a catchment (Riggs and Harvey, 1990). Consequently, the large size of the Ottawa basin, compared to its tributaries, could explain the relatively low CV of 0.53 at the mouth of the river. However, the CV for upstream stations does not increase as would be theoretically expected by Riggs and Harvey (1990). In fact, the CV decreases to a minimum of 0.37 at Rapides Des Quinze, just northeast of Lake Temiskaming, where the gross drainage area is roughly six times smaller than that at the mouth. This is the result of flow regulation. Reductions in flow variations due to hydro-electric operations are also evident for some tributaries, particularly the highly regulated Rivière Gatineau which has the lowest CV of all the tributaries in the basin, with a value of 0.39. All the tributaries with CV

below 0.95, with the exception of the Rivière Dumoine, contain large unnatural reservoirs in their basins.

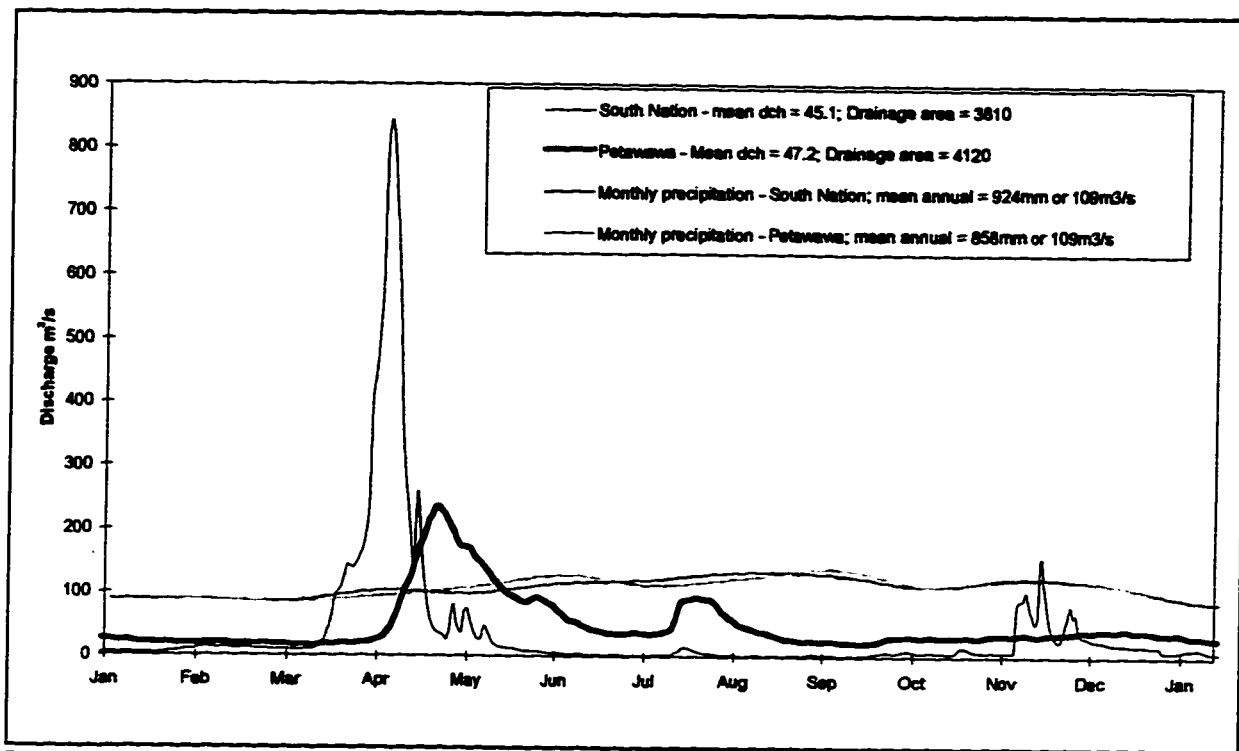


Figure 4-6: Mean daily discharge for two tributaries with similar drainage area and monthly precipitation, 1983-84.

Relatively unregulated tributaries, in this case those with CV above 0.95, have a wide range of CV which cannot be explained by basin size, or slope. Instead, their variation is most likely controlled by the geology and the active water storage capacity of the basin. Saxton and Shiau (1990) discussed the role geological materials and related vegetative cover of a catchment exert on flow variability, and conclude that their influence can be a primary one. They show that the nature and the structure of geological materials in a catchment controls the amount and the rate of infiltration of water through soils, its subsequent movement in the groundwater system, and ultimately its flow into streams. High infiltration rates and high ground water velocities produce low variability streamflow. Major aquifer storage and major surface storage capacities can also dramatically affect the variability of stream flow. The St.

Lawrence River, which drains the enormous Great Lakes, is a classic example of the effect that surface storage has on the variability of stream flow. It has very regular flow and a CV of 0.13 and much of its variation is due to the influence of tributaries, primarily the Ottawa River, downstream of the Great Lakes. Due to an abundance of lakes and swamps, surface storage capacities of basins situated in the Canadian Shield physiographic region can be large and the flows of rivers draining these areas can therefore be significantly moderated (Environment Canada, 1978).

Figure 4-6 illustrates the strong difference in flow regimes for the Petawawa and South Nation Rivers, two tributaries with similar gross drainage area and monthly precipitation but substantially different physiographic and land use characteristics. The South Nation River basin is underlain by 68% carbonate rocks, 31% clastic rocks and 1% metasedimentary rocks and is thickly covered by glacial till and glaciomarine clays, whereas the Petawawa River is underlain by 99% igneous, plutonic and metamorphic gneissic rocks and 1% carbonates and has only thin intermittent till cover. Vegetation and land use in the two basins also differ strongly, with the Petawawa almost entirely covered by mixed-wood forests of dominantly hard maple and white pine exploited by the forest industry and the South Nation containing only 20% forested areas dominated by white spruce and red pine, the remaining area being extensively used for agriculture. Surface water storage capacity is difficult to ascertain but a rough estimate can be had from open surface water area, the Petawawa basin having a total of 2.45% and the South Nation containing a much lower 0.34%. The estimates for open surface water area come from AVHRR data (Manitoba Centre for Remote Sensing,

1993) with a maximum resolution of 1km^2 , thus the applicability of these estimates is limited (see table 3-1 for more details on these basins).

Clearly, the nature of flow in the two basins differs strongly, with the South Nation River being characterized by extreme flow events in the spring and fall separated by very low baseflow periods and the Petawawa having more moderate peaks and substantially higher baseflow during seasonal lows. The South Nation River has the highest variation of flow among the tributaries studied with a CV of 2.39. The variation of flow in the Petawawa River, with a CV of 1.03, is slightly below the average of the remaining unregulated tributaries. These characteristics are contrary to the general rules of flow variation discussed by Riggs and Harvey (1990). Based on these rules, the South Nation River with a much lower basinal slope and more moderate climate should have had more moderated flow than the Petawawa. The differences can be explained by the differing nature of the geological materials, the different surface water storage capacities, and by the different uses of land of each basin.

4.1.4a The role of geology and water storage capacity

As discussed in the introduction (sections 1.5 & 1.6), the Leda clay deposited in the Champlain Sea roughly 10,000 years ago and glacial till that underlie parts of the South Nation basin have very low hydraulic conductivity, low infiltration rates, and low ground water velocities with the possible exception of the upper "weathered zone" (Farvolden and Cherry, 1988). Pumping tests demonstrate these properties (Edwards and Jones, 1993). Hydraulic conductivities, infiltration rates, and ground water flow velocities for the Petawawa basin on a regional scale are less well known and, as discussed earlier in the introduction, are subject to some controversy. However, it is agreed that shallow flow systems exist and behave

in a similar manner to that of porous media environments, although the strong structurally controlled anisotropic flow makes determinations of regional hydraulic conductivities difficult. Given these conditions, as well as the greater surface storage capacity of the Petawawa basin, it seems reasonable to conclude that the Petawawa basin has greater active water storage capacity than the South Nation basin. As a result, when precipitation occurs (rain or snowmelt), the infiltration capacity of the South Nation basin is easily exceeded and overland or shallow interflow in the upper weathered zone rapidly moves into the river causing a rapid increase in discharge. The Petawawa basin, with a higher capacity to absorb incoming precipitation due to either a more pervious groundwater system or greater surface storage capacity or both, has a less variable hydrograph.

4.1.4b The role of vegetation

The role of vegetation is difficult to interpret. Most of what is known about the effects of vegetation on hydrology comes from experimental catchment studies. McCullough and Robinson (1993) give an excellent review of these studies. They state that one of the biggest dilemmas with forest hydrology studies is the problem of scale. Most experimental studies are limited to 80ha for logistic reasons and extrapolation to larger basins may not be reasonable in many cases. They also caution against many popular beliefs about the effects of forests on hydrology. These can be summarized as follows:

- there is no evidence, apart from occult precipitation (where trees scavenge atmospheric water from fog in mountainous areas) that forests increase or decrease rainfall in any way;
- forests may reduce small floods in small catchments but not extreme events and not for large catchments. This includes the effect of moderating the rate of snow melt;

- forests may reduce erosion but the increased erosion rates attributed to deforestation are grossly exaggerated. Destructive logging techniques and land use practices, such as crop tilling, are more responsible for increased erosion than the lack of trees;
- forests do not augment low flows. In most cases they reduce flows due to increased interception and transpiration;
- forests do not necessarily evapotranspire more water than alternative crops. It is dependent on the species and the condition of the forest. Old forests, or those damaged by pollution, have a reduced ability to transmit water to the atmosphere;
- despite the higher infiltration and water storage capacities of forest soils, generally gains are lost to increased interception and transpiration;

Heatherington (1987) confirms the existence and falsity of these popular beliefs in a Canadian context.

Bosch and Hewlett (1982) reviewed 94 deforestation/reforestation catchment experiments and concluded that deforestation initially always caused increases in runoff, but the duration of the effect depends on the climate, with recovery more rapid in areas of high precipitation due to rapid growth rates. The removal of coniferous forests causes greater increases than the removal of deciduous forest which, in turn, was greater than removal of grasses or scrub, although these differences also vary with climate. Saxton and Shiau (1990) state that often the effects of vegetation changes are short-lived, because the replacement vegetation usually has similar characteristics and thus the streamflow remains relatively unchanged. Lockwood and Sellers (1983) determined the runoffs, transpiration losses and interception losses from areas covered by wheat, pine, oak, and grass using a numerical

model. According to their findings, summarized in Table 4-1, areas covered primarily in coniferous forest will lose the most water to the atmosphere.

	Runoff	Interception loss	Transpiration	Total losses
Wheat	417	158	134	282
Pine	152	253	308	562
Oak	279	172	263	435
Grass	318	62	335	397

Table 4-1: Annual totals of simulated runoff, interception loss, and transpiration for four vegetation types (in mm rainfall equivalent) (reproduced from Lockwood and Sellers, 1983).

Speculatively, vegetative cover neither substantially increases or decreases runoff in either basin. As well, agricultural practices in the South Nation River that could render the basin more prone to high discharge variability are probably nullified by the basin's low slopes. This suggests that any vegetative effects on the flows of the two basins are secondary to that of geology.

4.1.4c Relative importance of basinal characteristics on flow

To clarify the relative importance of different basinal characteristics on the nature of flow, the correlation of CV and basinal characteristics was investigated. Table 4-2 lists the results.

Characteristic	Correlation Coefficient	Frequency (# of subbasins containing the characteristic)
Reservoir Capacity	-0.94	7
Average Altitude	-0.79	16
Abundance of Deciduous Forest	-0.50	16
Abundance of Mixed Wood Forest	-0.43	16
Abundance of Surface Water Area	-0.42	16
Abundance of Plutonic Rocks	-0.37	16
Abundance of Metasedimentary Rocks	-0.28	16
Abundance of Coniferous Forest	-0.21	16
Abundance of Volcanic Rocks	0.11	16
Abundance of Carbonate Rocks	0.82	16
Abundance of Agricultural Land	0.84	16
Abundance of Clastic Rocks	0.87	16

Table 4-2: Correlation coefficient of characteristics of tributary basins versus CV (coefficient of variation) of discharge, in order of increasing correlation coefficient.

Since many basinal characteristics are related to each other, statistical dependencies can be strong and the interpretation of correlations must be done with caution. The abundance of open surface water (an approximation of the abundance of lakes) correlates negatively with CV, presumably indicating that greater water storage capacities produce lower flow variation. The abundance of forests correlates negatively with CV, presumably suggesting that the presence of forests has a moderating effect on flow. By the same token, the abundance of agricultural land has a strong positive correlation with CV, presumably suggesting that agricultural practices (usually accompanied by the removal of forests) increase the variability of flow, possibly by increasing the likelihood of overland flow during major storms or snowmelt events as has been suggested by many authors. However, the distributions of lakes, forests, and agricultural land, are themselves often ultimately controlled by the types of geological materials underlying a basin. Areas underlain by igneous and metamorphic rocks produced little glacial drift during the Pleistocene glaciation and consequently contain numerous lakes and are difficult to farm, rendering them more suitable for growing and harvesting forests. Areas underlain by clastic and carbonate rocks, and to a lesser extent volcanic rocks, are overlain by thick glaciogenic deposits which contain few lakes but are easily farmed rendering them more suitable for agricultural practices than for growing trees. This explains why igneous and metamorphic rocks correlate negatively with CV, along with the abundance of forests and the amount of open surface water and why clastic, volcanic, and carbonate rocks correlate positively with CV along with the amount of agricultural land. Thus, there is a dependency among these variables such that the presence or lack of forests or agricultural land and the abundance of lakes is confounded with the distribution of geological

materials, rendering the cause and effect relationships more difficult to ascertain. It is likely, however, that since flow variation is primarily controlled by the active storage capacity of a river basin (Riggs and Harvey, 1990), geology and its related physiography (abundance of lakes and permeability) must be a more primary control on flow variation than those factors that have lesser abilities to alter the overall storage capacity of an area, such as vegetation or landuse practices. This implies that the strong correlations between CV and abundance of forest and agricultural land are the result of their dependency on geology and that geology, of all variables, is the primary control on flow variability, after climate. Finally, reservoir capacity has an almost perfect negative correlation with CV, indicating the strong impact that flow regulation and artificial increases in storage capacity have on flow variability. Thus, natural flow variability in the Ottawa basin is dominantly controlled by its geology but this control is superseded by human signals for domains where large reservoirs have been built.

4.1.5 Time Series Analysis

4.1.5a Autocorrelation

In this study, autocorrelation was used to examine the periodicity of both regulated and unregulated discharge at lags totaling 4 years for the mouth of the Ottawa River and 2 years for other stations. This technique involves comparing a time series with itself at successive time intervals (lag). An essential pre-requisite for autocorrelation analyses is that the data exist in time at equal intervals (Davis, 1986). This is the case for daily discharge records. If the series is periodic, relatively large autocorrelation values will occur when the series has been shifted by one period, the phase shift necessary to re-align the signal. Autocorrelation is plotted as lag versus correlation coefficient, the latter ranging from a

perfect correlation of 1 to a perfect negative correlation of -1. Mathematically, autocorrelation is simply the standardized covariance of two variables, the series and itself, at given lags. The equation for autocorrelation of samples of a population is:

$$r_{\tau} = \frac{\sum Y_t Y_{t-\tau} - \sum Y_t \sum Y_{t-\tau}}{\sqrt{[\sum Y_t^2 - (\sum Y_t)^2][\sum Y_{t-\tau}^2 - (\sum Y_{t-\tau})^2]}} \quad (\text{after Davis, 1986}) \quad \text{Equation 4-1}$$

where τ is the lag step with the bounds $-1 < \tau < 731$ (days totaling 2 years), Y is the variable, t is the time step with the bounds $-1 < t < N+1$ where N is the number of data points. As lag increases, the autocorrelation is progressively calculated from fewer measurement pairs and therefore is less reliable. The time series here are long compared to the maximum lag, and therefore this effect is minimal. Figure 4-7 illustrates the autocorrelation function of some idealized time series in order to assist in interpreting the autocorrelograms presented next.

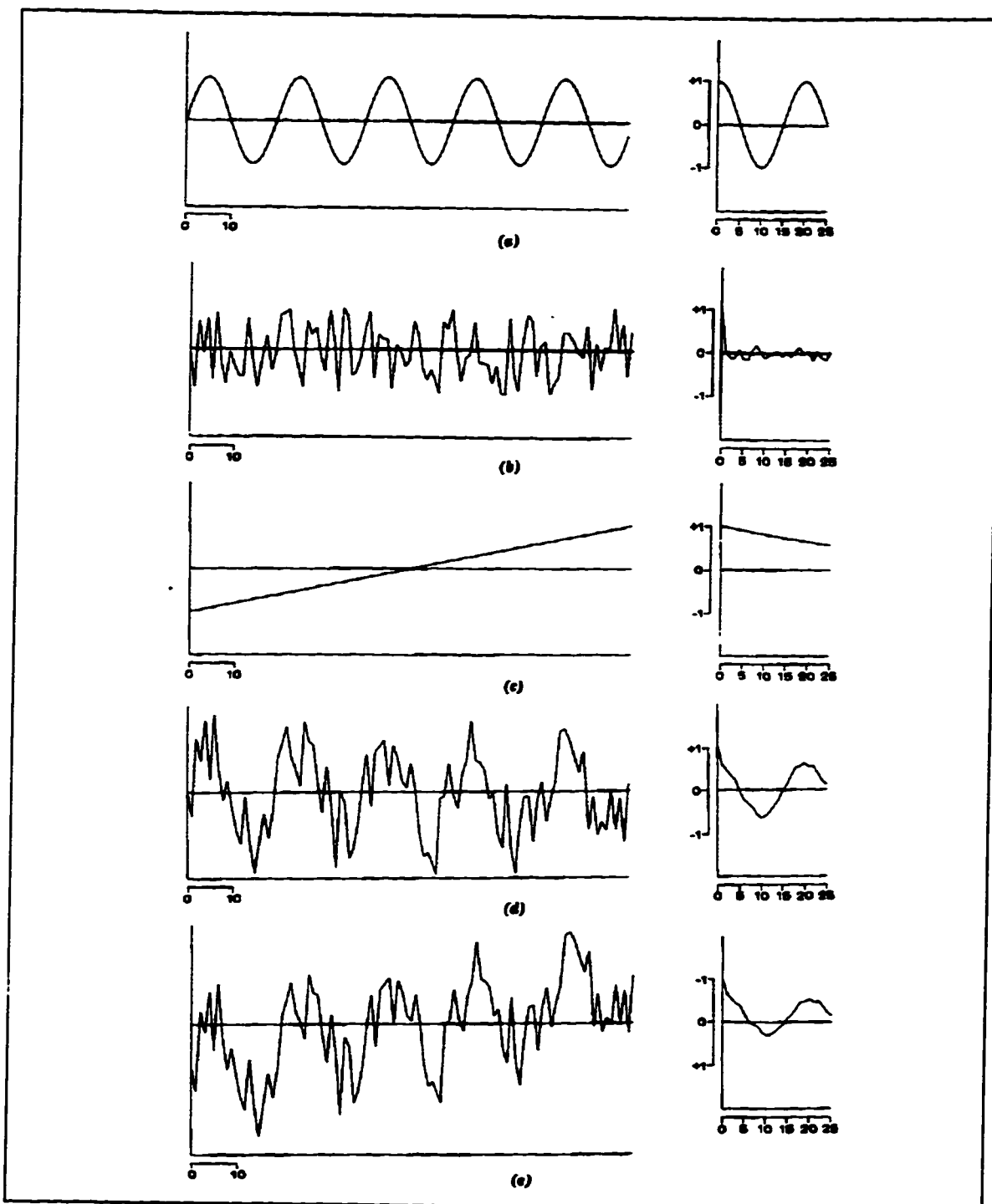


Figure 4-7: Some idealized time series and their autocorrelation functions. (a) Sine wave with wavelength of 20 units. (b) Sequence of random numbers of noise. (c) Sequence of linearly increasing numbers or trend. (d) Sine wave plus random noise (sequence a plus sequence b). (e) Sine wave plus random noise plus linear trend (sequence a plus sequence b plus sequence c). (From Davis, 1986)

4.1.5b Annual signal

As shown in Figure 4-8, autocorrelation of the discharge at the mouth of the Ottawa River shows one prominent annual cycle which produces strong autocorrelation peaks at lags of 365, 730, 1065, and 1430 days and almost certainly at greater multiples of 365. The first-order autocorrelation (lag 1 day) has a value of 0.989 and after 10 days, the autocorrelation coefficient drops below 0.8. The periods of strong positive autocorrelation have a duration of roughly 80 days, 40 of those approximately representing maximum autocorrelation (above 0.4 autocorrelation coefficient). The river very weakly correlates negatively with itself at lags of 110-150 and 240-280 days. And at lags of roughly 80-100 and 300-320 days, discharge does not exhibit significantly meaningful correlation.

These results strongly suggest that periodicity in the discharge signal is dominated by a yearly cycle, supporting the visual interpretation of the hydrograph earlier in this chapter. In other words, all periodic events in the discharge signal operate only on a yearly basis. These include the obvious high water stand produced by spring thaw, the low water stand in the fall and winter, and the late fall rise. The weakly negative correlations represent times when the discharge signal is out of phase with itself such as would occur if the low water stand in September were superimposed on the spring flood in April. They occur at 4-5 months and 8-10 months lag.

The duration of positive autocorrelations yield some useful information. They suggest that the discharge of the Ottawa River is very stable over periods of 10 days and relatively stable for periods of up to 40 days.

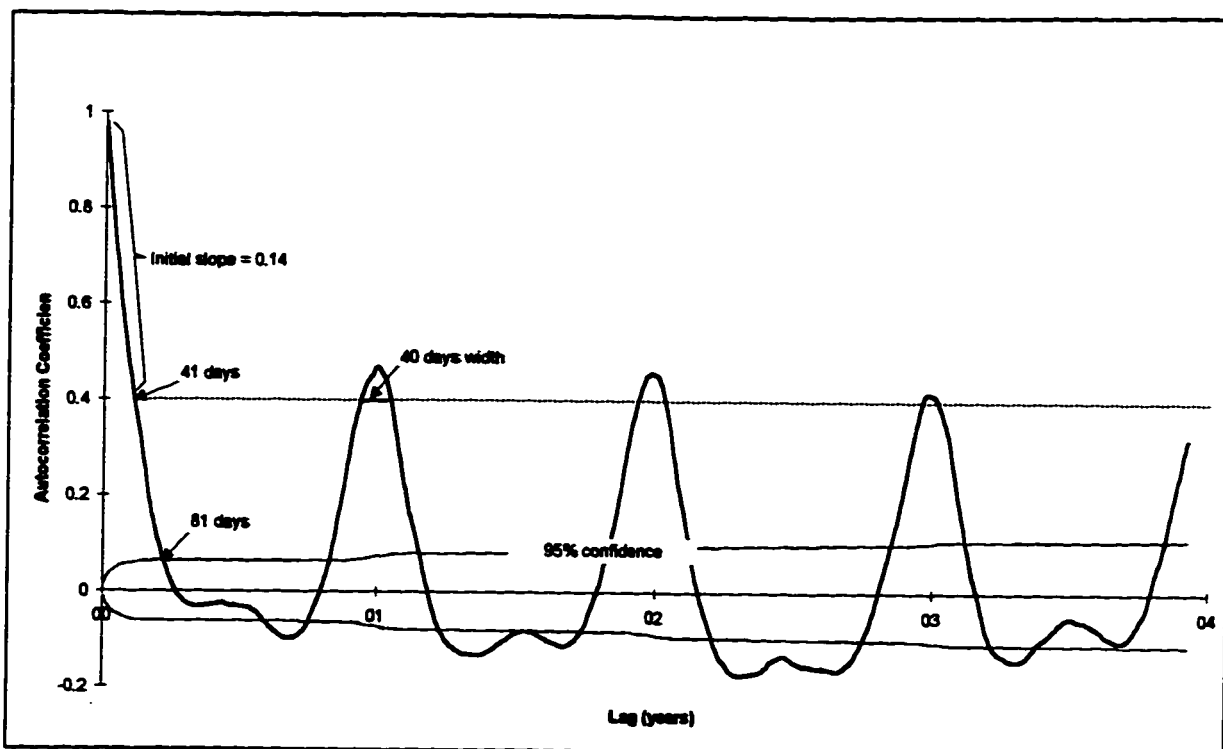


Figure 4-8: Autocorrelogram for discharge at the mouth of the Ottawa River.

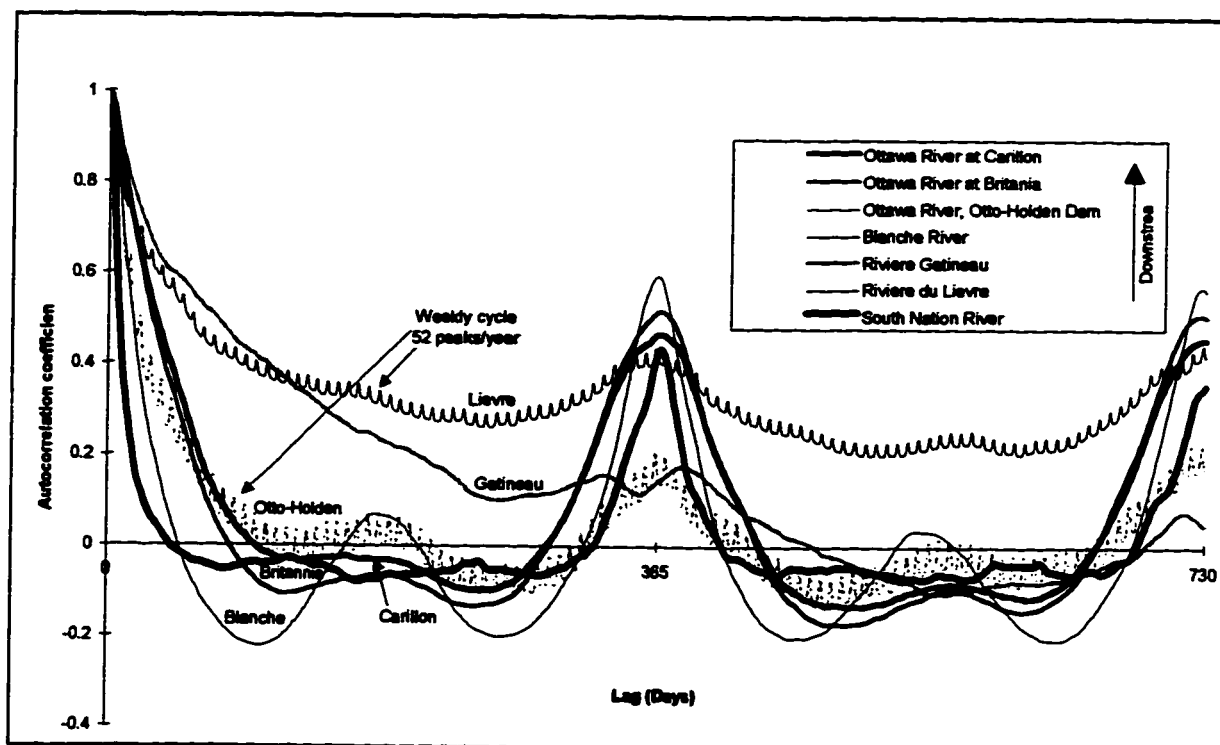


Figure 4-9: Autocorrelograms of discharge for selected stations in the Ottawa River basin.

Similar autocorrelograms exist for other gauging stations on the Ottawa River and for most of the tributaries. Some of these are shown in Figure 4-9. The amplitude of the Blanche

River autocorrelogram is considerably greater than that of the Ottawa River mouth. The same is true for the rate of change of its autocorrelation coefficient, dropping below 0.8 after 6 days. These characteristics imply that this river, having larger autocorrelations at annual lags, is more strongly seasonally controlled than the Ottawa but the stability of its discharge is restricted to a smaller range. The South Nation River, also shown, is similar to the Blanche in its rapid decline of the autocorrelation coefficient, dropping below 0.8 in only 3 days, but exhibits weaker seasonal control, correlating with itself less strongly than the Blanche or the Ottawa on an annual basis. It also exhibits no negative correlations at lags of 4-5 and 8-10 months as the Blanche and Ottawa River mouth do, suggesting that the seasonal fluctuations of this river occur more randomly in time than those of other tributaries. Table 4-3 summarizes some relevant characteristics of the autocorrelograms for the Ottawa River and for tributary gauging stations, and Figure 4-10 is a map of the data contained in the table allowing the relative stability of discharge in the Ottawa Basin to be visualized.

River Name	First order autocorrelation coefficient	Days required for the ACC to drop below 0.8	ACC at lag 1 year
Main River			
Reservoir Dozois	0.987	13	0.445
Lac Granet	0.997	19	0.241
Barrage de Rapide-Sept	0.967	10	0.087
Ottawa	0.953	8	0.082
Barrage Des Rapides Des Quinze	0.986	11	0.109
La Cave Rapids	0.922	5	0.178
Des Joachims	0.951	8	0.219
Chats Falls	0.988	11	0.475
Barrage de Carillon	0.979	11	0.466
Tributaries			
Blanche	0.984	7	0.585
Montreal	0.889	3	0.424
Mattawa	0.983	5	0.395
Dumoine	0.983	14	0.535
Petawawa	0.996	11	0.623
Coulange	0.988	8	0.571
Bonnechere	0.974	10	0.551
Madawaska	0.925	8	0.448
Mississippi	0.996	12	0.605
Rideau	0.977	5	0.478
Gatineau	0.976	15	0.141
Lievre	0.951	9	0.417
Petite Nation	0.987	12	0.606
South Nation	0.981	3	0.421
Rouge	0.988	7	0.526
Nord	0.991	8	0.513

Table 4-3: Some characteristics of the autocorrelagrams for the Ottawa River and for tributary gauging stations.

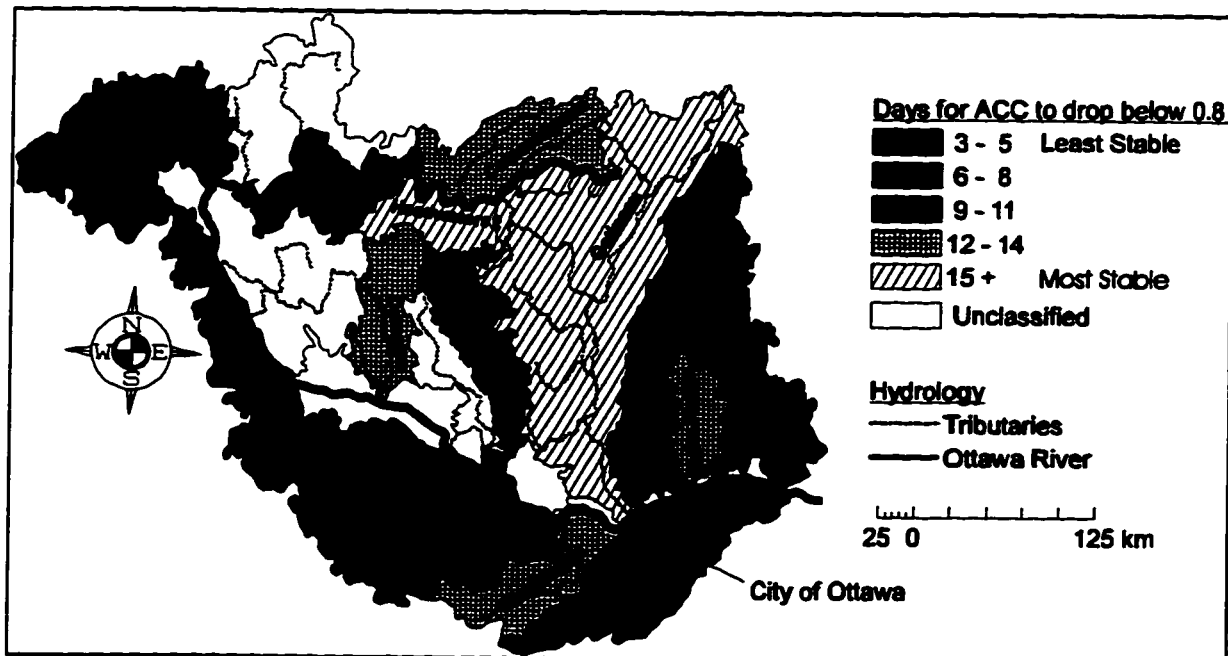


Figure 4-10: Relative stability of discharge based on autocorrelation of discharge.

4.1.5c Short term cycles

The autocorrelograms of the Rivière du Lievre, and Cave Rapids generating station, are also shown in Figure 4-9. Both the Lievre and Cave Rapids contain 52 regularly spaced small peaks with equal amplitude per year in their autocorrelograms. These seven day cycles are the result of hydro-electric generating stations varying the flow of water in synchronicity with the demand for electricity, in this case decreased usage of electricity on weekends. The Montreal River, Des Joachims station, and Rapide Sept station also exhibit this signal. The Carillon generating station at the mouth of the Ottawa River is a baseload station, supplying a constant amount of electricity to the regional grid, it does not have a large reservoir with which to store water for later release, and consequently does not have a seven day cycle. It may in fact have a very weak one, but it is undetectable by autocorrelation. Powis (1995) analyzed river discharge using spectral analysis, a more sensitive technique for detecting cyclicity in time series, and discovered weak seven day cycles in the discharge of baseload hydroelectrical generating stations, not evident in their autocorrelograms. However, as some of the data used were back calculated from power generation records, the detected cyclicity may be artificial. Powis also notes that the cyclicity could be the result of cyclical discharge loading upstream. Whatever the case, no volumetrically important short term cycles exist in the discharge of the Carillon generating station, or the Britannia gauging station 75 km upstream, suggesting that any upstream cyclical discharge loading has been obliterated by the natural dampening processes of turbulent flow and influxes of non-cyclical flow from tributaries by the time water reaches lower stretches of the river. It should also be noted here that it is not possible to detect one day cycles with mean daily discharge records. These may

exist at "peaking stations", hydro-electric stations which supply electricity only at peak hours of the day. The Lower Notch generating station on the Montreal River is such a station.

4.1.5d Highly regulated discharge

The autocorrelogram of the Rivière Gatineau is markedly different from any other shown in Figure 4-9. Its autocorrelation gradually decreases throughout the year and shows almost no annual autocorrelation peak. Of all the tributaries, it has the lowest autocorrelation at a lag of 1 year and the lowest rate of change of autocorrelation, requiring 15 days to drop below a value of 0.8 and remaining above a value of 0.4 for 105 days. The Rivière Gatineau also has the lowest CV of any of the tributaries. This is the product of highly regulated discharge. This river is the largest tributary in the basin but also contains the largest reservoir, the Baskakong with a total capacity of 2.65 km^3 or 25% of the river annual discharge. The reservoir is large enough to completely dampen natural seasonal fluctuations, producing perfectly regular flow. The hint of seasonality seen in the autocorrelogram is produced by the influx of unregulated flow downstream from the reservoir.

The Rivière du Lievre, having a total reservoir capacity of 1.7 km^3 or 32% of its annual discharge and supplying water to 5 separate hydro-electric generating stations, is even more regulated than the Rivière Gatineau. As shown in Figure 4-7, the autocorrelogram for a constant value through time is a straight line with autocorrelation of 1. In a similar manner, the discharge from the Rivière du Lievre is so regulated that its autocorrelation does not drop below 0.3 for 2 years. The slight increase in autocorrelation seen at a lag of 1 year may be due to reservoir capacity being briefly exceeded in the spring as well as to inputs from unregulated tributaries, yielding some seasonal variation in discharge.

4.1.5e Crosscorrelation

Crosscorrelation is very similar to autocorrelation in that the covariance of two time series is calculated at progressive lag. The major difference being that instead of comparing a series with itself, crosscorrelation compares two separate series. Since the two series are not identical, as they are in autocorrelation, the crosscorrelogram does not have a perfect correlation at lag 0 but instead gives the linear standardized covariance of the two data series. Also, the crosscorrelogram is not symmetrical about lag 0 and so both positive and negative lags must be considered. The equation for crosscorrelation is:

$$r_m = \frac{n \cdot \sum Y_1 Y_2 - \sum Y_1 \sum Y_2}{\sqrt{[n \cdot \sum Y_1^2 - (\sum Y_1)^2][n \cdot \sum Y_2^2 - (\sum Y_2)^2]}} \quad (\text{After Davis, 1986}) \quad \text{Equation 4-2}$$

where m is a given match position occurring as one variable is shifted relative to the second by a given lag. The number of data points being compared at one match position is equal to n .

4.1.5f Spatial and temporal flow in the Ottawa River

Temperature varies through time and space in the Ottawa River basin. For example, the average temperature in April is 8.5°C and 12.5°C in the northern Blanche and southern Rideau basins, respectively. The distribution of precipitation (quantified in a later section) also varies spatially and temporally within the basin. These climatic variations, combined with variations induced by hydro-electric installations, are manifest in the timing and location of discharge events throughout the basin. Figure 4-11 is a crosscorrelogram of discharge at the mouth of the Ottawa River and some upstream gauging stations. Lag 0 can be thought of as the time that discharge events occur at the mouth of the river. Negative lags represent events that occur after those at the mouth and vice-versa. The numbers on the figure represent the lag at the time of maximum crosscorrelation coefficient, revealing the along-river timing of

discharge events such as the spring thaw. This technique utilizes a moving time reference which is sensitive to annual climatic variations - discharge at the mouth of the river - and thus provides a different perspective than the techniques based on calendar dates.

Discharge events occur at later times upstream, from the mouth at Carillon to Barrage Des Quinze just northeast of Lake Temiskaming. Further upstream, the impact of hydro-electric installations is much greater and the flows are out of phase with nature. Weekly cyclicity caused by power generation fluctuations, discussed earlier, is visible in the signals of the Rapides Des Joachims and Cave Rapids stations. The strength of the correlations decrease in an upstream direction but all are greater than the 95% confidence interval, meaning that, on average, 19 times out of 20 the observed crosscorrelation values are greater than would be expected due to chance.

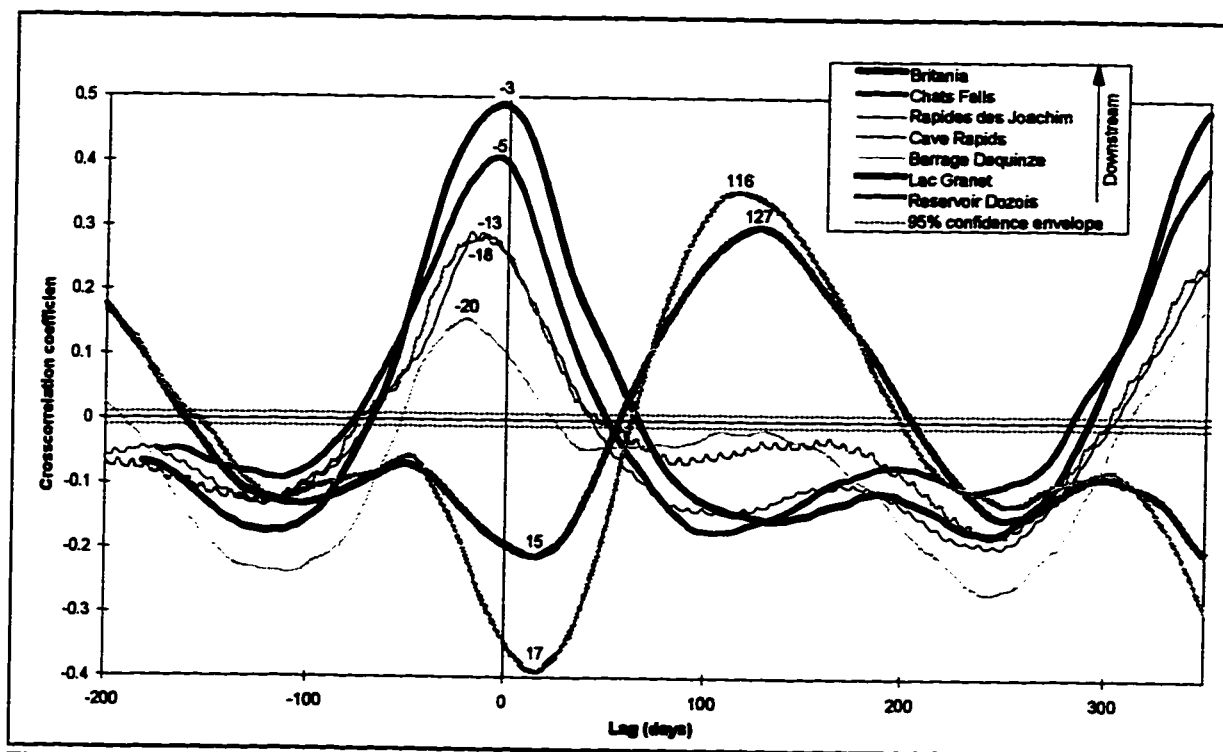


Figure 4-11: Crosscorrelation of daily mean discharge at the mouth of the Ottawa River with some upstream stations.

From this analysis the relative timing of discharge events can be extracted. The spring thaw, being the most dominant discharge event and representing the majority of the variance in the discharge signal, will be used as an example. Spring thaw occurs at the mouth of the river 3 days earlier than at Britannia, 5 days earlier than at Chats Falls, 13, 18, and 20 days earlier than at Rapides Des Joachims, Cave Rapids, and Barrage Des Quinze, respectively. Spring thaw for stations further upstream will occur roughly 4 months before that of the mouth. In other words, in the headwater reaches of the river, a "spring thaw" signal occurs in the early winter (December - January). However, the crosscorrelation does not represent only spring thaw. It is the product of comparing an entire yearly discharge at one location with the entire yearly discharge at another and so events at other times of the year, such as summer drawdown or fall rise are also represented by this analysis. In some instances, such as the summer drawdown, this will strengthen the relationship described above. In others, such as the fall rise, that likely occurs in the reverse order to the spring thaw, the crosscorrelation is weakened. In this sense then, without filtering the dataset, the crosscorrelogram is useful only for determining the timing of the dominant events in the discharge cycle.

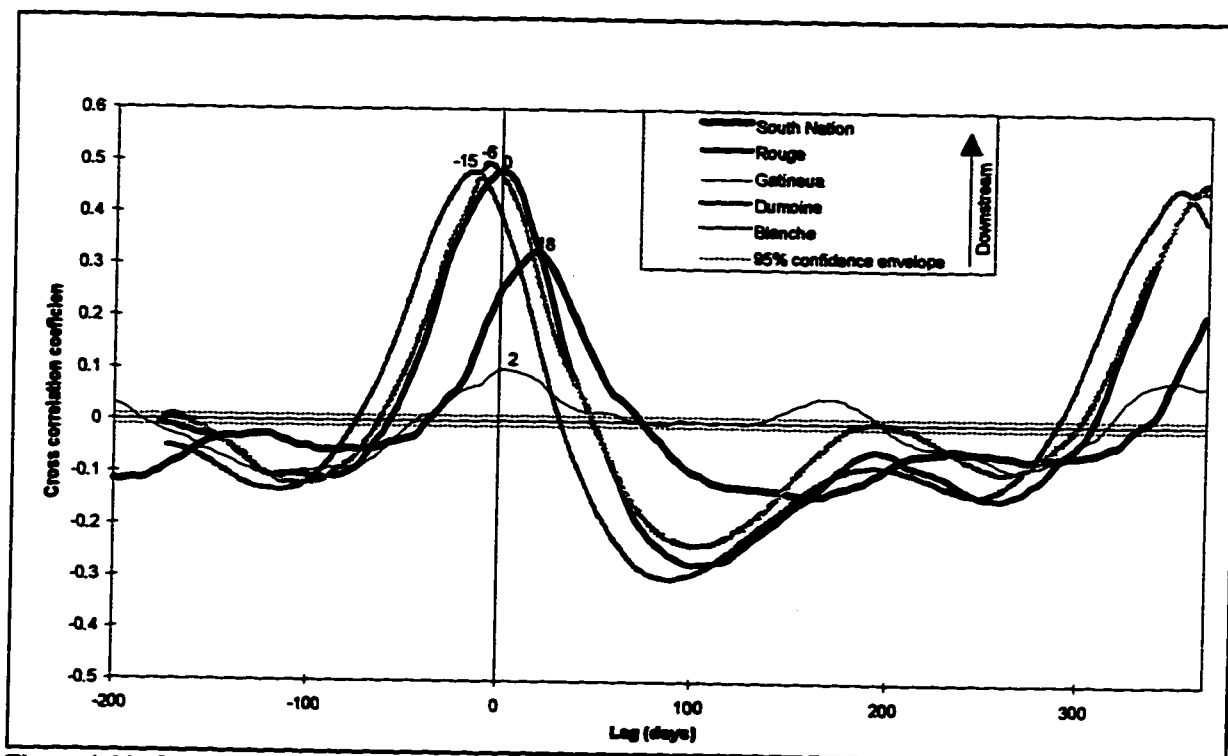


Figure 4-12: Crosscorrelation of daily mean discharge at the mouth of the Ottawa River and some of its major tributaries.

4.1.5g The timing of tributary input

Crosscorrelating the discharge of the mouth with that of the tributaries produces a similar crosscorrelogram (Figure 4-12). From this plot we can see the average timing of the dominant discharge event (spring thaw in most cases) in the tributaries relative to that at the mouth of the Ottawa River. Table 4-4 summarizes this information for all tributaries and includes that for Ottawa River stations as well. In order to visualize these results spatially the lag per tributary basin was mapped (Figure 4-13). The timing of spring thaw is dominantly controlled by temperature, which, in turn, varies with latitude, altitude, and probably to some degree by proximity to Lake Ontario. These factors are born out in the results of the crosscorrelation. The Dumoine River thaws roughly 15 days after time 0, spring thaw at the mouth of the Ottawa River. This is due to its northern position and relatively high average altitude of 366m. Also it is not proximal to Lake Ontario. The Blanche River, which has a

northerly position but a relatively lower average altitude of 280m, floods, on average, only 6 days after the mouth. The Rouge River, with an average altitude of 357m and a relatively southern position discharges roughly in synchronicity with the mouth. The South Nation River has its spring thaw roughly 18 days earlier than the mouth due to its southern latitude, proximity to Lake Ontario and a low average altitude of 78m. This implies that the South Nation River floods roughly 1 month (33 days) before the Dumoine River. Table 4-4 also lists maximum crosscorrelation coefficients and it can be seen that they vary considerably. In general, regulated tributaries have lower crosscorrelation coefficients. This is due to the dampening of seasonal fluctuations. The Rivière Gatineau exemplifies this best, having a crosscorrelation coefficient of only 0.099 at a lag of 2 days. The timing of flows from regulated tributaries is therefore less certain than that of unregulated ones. The South Nation River which also has a low crosscorrelation with the mouth of the Ottawa River is a different case. Due to the nature of its catchment and situation within the basin, discussed earlier, its spring flood occurs rapidly and less regularly in time than that of most other tributaries. As such, its crosscorrelation with the mouth of the Ottawa River is naturally lower.

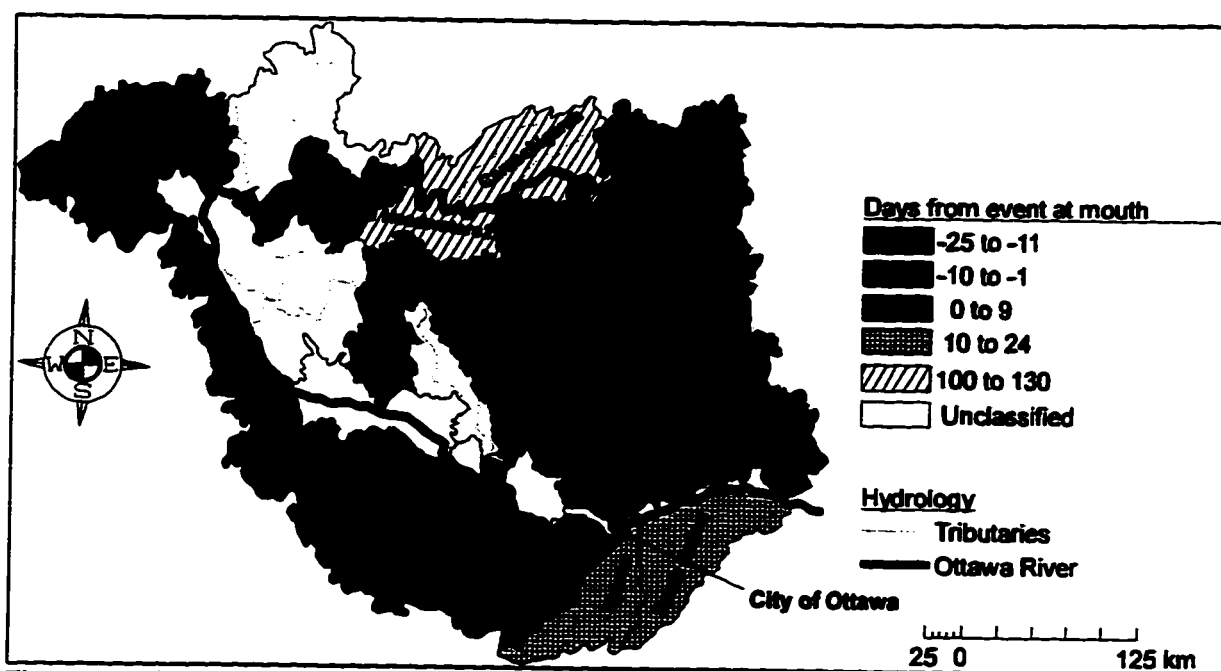


Figure 4-13: Timing of dominant discharge events to the Ottawa River.

Ottawa River stations in order of increasing distance upstream.	Maximum crosscorrelation coefficient	Lag (days) at Max
Britannia	0.489	-3
Chats Falls	0.408	-5
Des Jochims	0.290	-13
Cave Rapids	0.291	-18
Barrage Des Quinze	0.157	-20
Lac Granet	0.301	127
Reservoir Dozois	0.355	116
Tributaries in order of increasing lag		
Lievre	0.277	-17
Dumoine	0.473	-15
Montreal	0.370	-14
Coulange	0.384	-12
Petawawa	0.411	-8
Petite Nation	0.569	-7
Blanche	0.497	-6
Rouge	0.482	0
Bonnechere	0.379	2
Gatineau	0.099	2
Mississippi	0.398	3
Mattawa	0.422	5
Madawaska	0.328	7
South Nation	0.328	18
Rideau	0.380	21

Table 4-4: Peak crosscorrelation coefficients and the lag at which they occur.

4.2 WATER FLUXES

The partition of rainfall into interception, evaporation, transpiration, infiltration, and runoff is controlled mainly by the interfaces between the lithosphere, the biosphere, the atmosphere, and the hydrosphere (Braud et al., 1995). Attempts to model and understand the complex relationships between these spheres on both the local scale (Monteith, 1995; Wang and Doodge, 1994; Soegaard and Boegh, 1995) and in the context of global general circulation models (Sausen et al., 1994) have been numerous and met with varying degrees of success. A good review of these models can be found in Maidment et al. (1994, 1995). Saxton and Shiau (1990) and Riggs and Harvey (1990), referenced in earlier sections of this chapter, discuss some of the physical controls on these fluxes. Bonell (1993) reviews the process of runoff generation in forests and Berner and Berner (1987) give an excellent review and analysis of the global water cycle and the movement of water to and from its various reservoirs. Also the material in section 4.1.4b, the role of vegetation, is relevant to this section. The aim of the following data analyses is to quantify the temporal and spatial fluxes of water to and from the Ottawa River basin for later use in interpreting the river chemistry. In the process of doing this, some new techniques for quantifying water fluxes across the hydrosphere-atmosphere interface have been produced and may be of use in refining the inputs to some models.

4.2.1 Precipitation Distribution

Monthly precipitation for the basin was determined from meteorological data analyzed in SPANS GIS (see chapter 3). The spatial and temporal distribution of precipitation in the Ottawa Basin is shown in Figure 3-7. Area-cross tabulation of precipitation maps with the

tributary drainage basin boundaries produces rates and volumes of precipitation per tributary basin per month as well as for the year. Table 4-5 lists the results of this operation and Figure 4-14 illustrates the general pattern of precipitation in the basin. Precipitation is lowest in the winter months, January through April, with the basinal average at around 54mm per month. It increases in May to 70mm and then peaks in the summer months June through September with a basinal average of 85mm per month. The fall, October through December, receives an intermediate amount of precipitation, 73 mm per month.

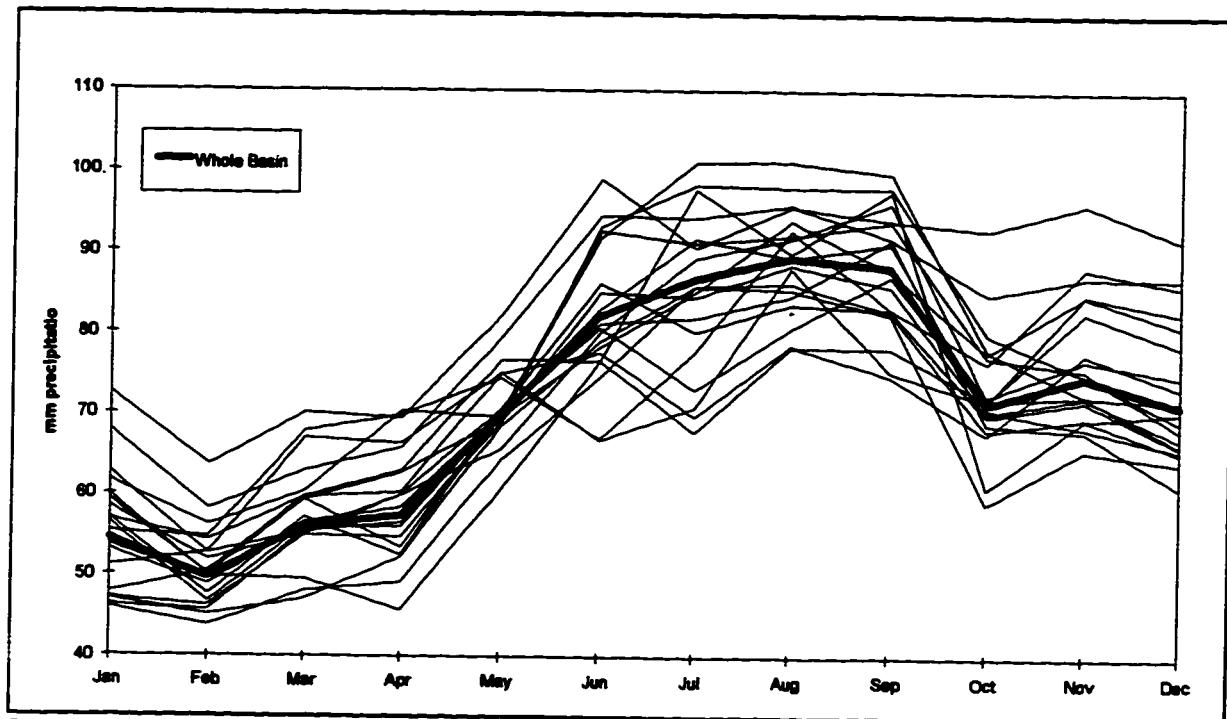


Figure 4-14: Precipitation per tributary basin and for the whole basin per month.

Tributary Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Gatineau	46	44	48	49	64	75	86	85	82	59	66	64	794
Lievre	47	45	47	52	69	79	86	86	83	68	70	66	832
Bonnechere	48	50	60	60	75	78	70	79	75	68	78	73	833
Noire	46	46	55	57	71	86	80	84	83	70	72	66	836
Montreal	57	47	56	56	70	81	82	85	92	69	68	61	838
Carnachigama	54	50	50	46	61	77	98	90	98	61	70	70	839
Coulonge	47	46	55	55	69	85	84	88	86	70	72	67	842
Petawawa	59	52	55	60	71	81	73	81	87	72	77	75	858
Madawaska	57	54	60	63	77	77	68	78	78	72	83	79	861
Blanche	60	50	59	53	70	83	82	89	91	71	69	66	870
Whole Basin	68	69	86	87	79	82	87	89	88	71	76	71	872
Mississippi	51	53	67	66	75	67	71	88	75	72	85	83	873
Mattawa	63	53	55	60	66	80	89	92	96	72	72	72	890
Dumoine	53	49	57	58	70	93	91	92	94	77	76	68	896
Rideau	55	55	68	70	74	67	78	93	83	76	88	86	911
Kanoevis	57	48	57	53	70	92	101	101	100	78	72	66	914
South Nation	62	56	60	70	70	78	85	94	88	78	85	81	924
Kipewa	59	50	59	63	69	93	98	98	98	80	75	69	931
Rouge	68	58	63	66	79	95	94	96	92	85	87	87	967
Petite Nation	73	64	70	70	82	98	91	96	94	93	96	92	1037

Table 4-5: Average precipitation per month for tributary basins and the whole Ottawa River basin (1920-1990), arranged in order of increasing annual precipitation.

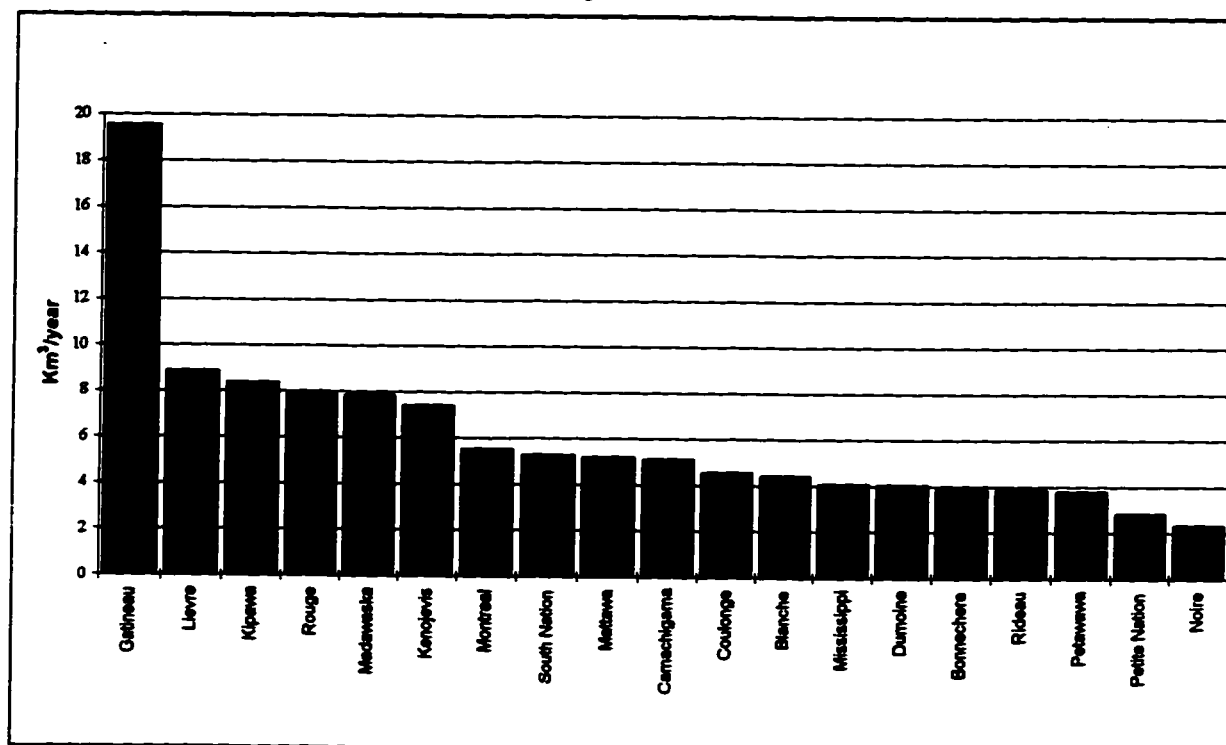


Figure 4-15: Volume of precipitation per year for tributaries of the Ottawa River.

Multiplying area by the average precipitation yields volumes of precipitation per tributary basin. Figure 4-15 graphically represents this result. The entire basin receives 130

km³ of precipitation per year. Of this, the Rivière Gatineau basin, receiving 19.5 km³, receives the lions share whereas the Rivière Noire, getting only 2.3 km³, receives the least.

4.2.2 Relationship of Precipitation and Discharge

Intuitively, variation in the precipitation rate is directly responsible for variations in discharge. Riggs and Harvey (1990) document many cases of how discharge responds to variations in precipitation rate for catchments with different climates and different physical characteristics. In an attempt to characterize the response time of discharge to precipitation in the Ottawa River basin, the daily meteorological record at Ottawa International Airport, one of the 60 used in this study, was crosscorrelated with discharge records of proximal tributaries and the mouth of the Ottawa River. It would have been more effective to crosscorrelate average daily precipitation per basin with the discharge of the same basins but it would involve enormous amounts of time and computer resources to produce daily precipitation maps for a period of 30 years (10950 maps) which would have to be subsequently area-crosstabulated with drainage basins (another 10950 operations). Indeed, creating the 13 used in this study was a lengthy process. It should also be noted that winter precipitation, which is primarily snow, and spring discharge, which is primarily snow melt, were not removed from the records before crosscorrelation. This undoubtedly, weakens the strength of the crosscorrelation.

The result of the analyses are shown in Figure 4-16. In this case, the discharge was crosscorrelated against precipitation and positive lags represent thus the time that a precipitation event occurred before a discharge event. The plot shows that the South Nation River maximum response to a major precipitation event at Ottawa International Airport begins almost immediately, peaks two days after the precipitation peaks, and shows no further

correlation after roughly 7-8 days. The Mississippi River shows a weak positive correlation after 2-3 days which gradually subsides. The other rivers all show weak negative correlation with precipitation at all lags. This is not surprising since generally, in the summer months, the increase in evapotranspiration outpaces the increase in precipitation and hence, on a regional scale over sustained periods, a negative correlation between precipitation and discharge should result. Even the South Nation River has a negative correlation with precipitation at greater lags. Why then does the South Nation River respond differently than the other rivers at short lags?

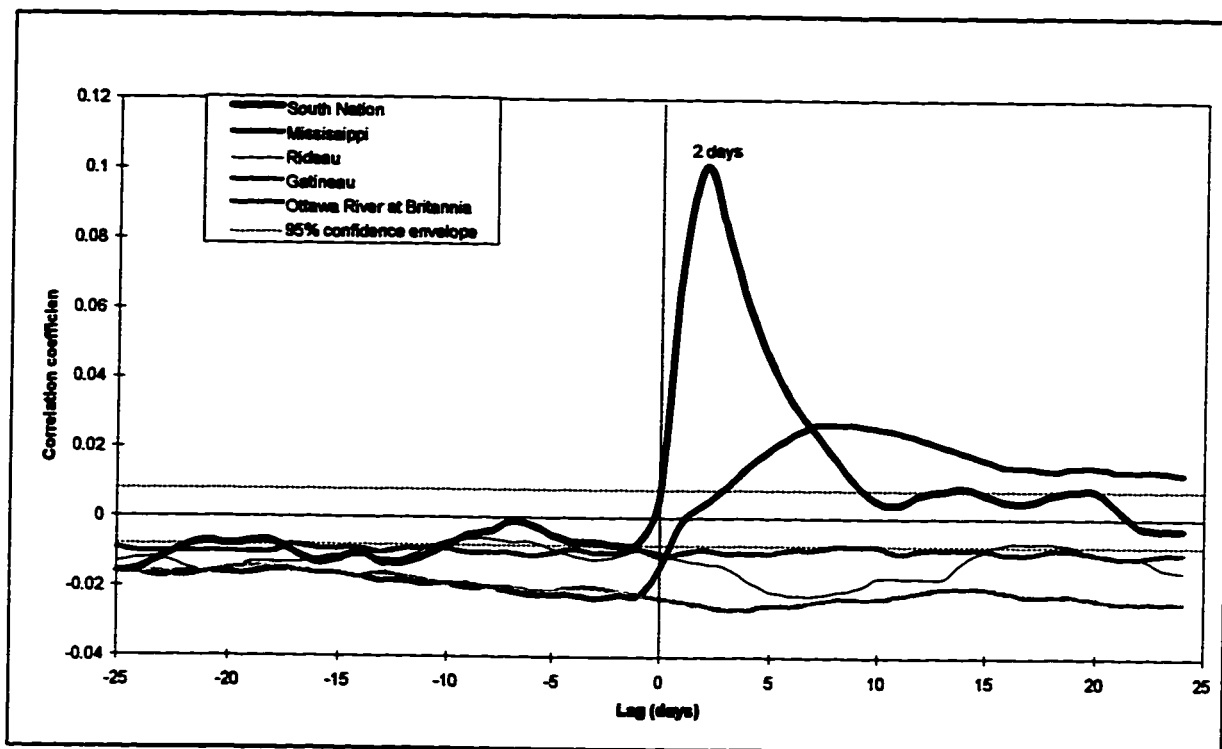


Figure 4-16: Crosscorrelogram of daily precipitation at Ottawa International Airport and daily discharge of proximal river gauging stations in the Ottawa River basin.

The first reason is probably proximity. Analysis of daily precipitation and temperature records over a period of 60 years at Ottawa International Airport and in Maniwaki, a town 150 km north of Ottawa on the Rivière Gatineau, reveals the following relationships:

$$Maniwaki(T) = 1.0067 \times Ottawa(T) - 2.14; \quad r^2 = 0.98$$

Equation 4-3

$$Maniwaki(P) = 0.55 \times Ottawa(P) + 1.07; r^2 = 0.33 \quad \text{Equation 4-4}$$

where T is temperature in °C and P is precipitation in mm. This shows that, on a daily time scale, precipitation is not a strongly regional event whereas temperature is. Therefore, basins that receive precipitation from distant areas or different climatic zones than that of Ottawa International Airport are unlikely to correlate strongly on a daily time scale. A Greater proportion of the South Nation River basin is proximal to Ottawa than that of the other basins, possibly with the exception of the Rideau River. However, judging from isoyets of annual precipitation, a greater proportion of the South Nation than the Rideau basin lie in a similar climate zone as the Ottawa International Airport.

Secondly, as discussed in section 4.1.4 of this chapter, of all the tributaries, the response to variations in water inputs is greatest and most rapid for the South Nation River due to the relatively impervious nature of its basin and its small water storage capacity. This means that on a daily time scale the South Nation River responds to precipitation strongly whereas other basins, which contain greater surface storage capacity or more pervious fill will respond more sluggishly or not at all, depending on the amount of precipitation that falls.

4.2.3 Evapotranspiration

Determinations of evapotranspiration through space and time are more difficult than those of precipitation and runoff, primarily owing to the much more dynamic behavior of the atmosphere than the hydrosphere. Nevertheless, it is relatively simple to determine the total evapotranspiration of humid watersheds over long periods of time (years or months). It is much more difficult to determine evapotranspiration for units of time and space other than those that govern watersheds.

For calculations of evapotranspiration from a watershed, the following formula can be used (Wisler and Brater, 1959):

$$E = P - Q - \Delta S \quad \text{Equation 4-5}$$

where E is total evapotranspiration, P is total precipitation, Q is discharge, ΔS is the change in ground water storage. Averaged over long periods of time, ΔS becomes zero leaving:

$$E = P - Q \quad \text{Equation 4-6}$$

In this study, all precipitation determinations were averaged over 60 years and discharge determinations were averaged over a minimum of 20 years and a maximum of 80 years, and changes in groundwater storage can therefore be neglected (equation 4-6).

As discussed in chapter 3, average precipitation for the Ottawa River basin was determined by GIS techniques and is calculated to be 130 km³ per year. From hydrological records, mean annual discharge from 1962 to 1992 is calculated to be 63 km³ per year. Average evapotranspiration for the Ottawa River basin is therefore calculated to be 51% of precipitation per year or 67 km³ per year. These figures are in agreement with the 50% calculated by Environment Canada (1978) and 51 % proposed by the Ontario Water Resources Commission and the Quebec Water Board (1971).

The GIS database constructed for these calculations allows the same evapotranspiration calculation to be done for each of the tributary basins with reliable discharge records. This calculation can be done on an annual, seasonal and monthly basis. Indeed, with more time and computer resources the calculation could be done on a daily basis. However, unlike precipitation, discharge is manifest from conditions over long periods of time, periods usually greater than one month and often greater than a season. Factors such as ground water flow rates, seasonal climatic loading, and those imposed by humans, namely the

direct alteration of river flows, typically operate on an annual basis, groundwater flow rates perhaps longer. In light of this, the calculation of precipitation minus discharge (equation 4-6) only represents evapotranspiration at time scales of one year or greater. At lesser time scales, the ΔS term in equation 4-5 becomes a factor and subtracting discharge from precipitation yields the combined term of evapotranspiration plus the change in ground water storage:

$$E + \Delta S = P - Q \quad \text{Equation 4-7}$$

we can therefore define a new term:

$$E' = P' - Q' = E + \Delta S \quad \text{Equation 4-8}$$

where E' equals precipitation (P') minus discharge (Q') at shorter time intervals than those required to reduce ΔS to zero. It can be thought of as seasonal water flux. Assuming that the equilibrium groundwater volume is defined over long periods by the relationships in equation 4-6, the following can be stated:

if $E' > E$, then ΔS is negative indicating groundwater drawdown;

if $E' < E$, then ΔS is positive indicating groundwater recharge;

if $E' = E$, then ΔS is zero indicating groundwater equilibrium.

Table 4-6 lists evapotranspiration per tributary basin per year (E) as well as the values of E' and the state of ΔS on a monthly basis. It is apparent that groundwater recharge occurs dominantly in the spring from snowmelt. The summer is the time of greatest evapotranspirative loss with values of E' often twice those of annual evapotranspiration (E) and thus represents a period of groundwater drawdown. The winter is also dominantly, although less strongly, a period of groundwater drawdown due to the fact that incoming precipitation is temporarily stored as snow. The fall represents a period of relative

groundwater equilibrium or moderate recharge where evapotranspirative losses are roughly equal to the annual ones. Flow augmentation practices confound determinations of E , ΔS and E' by this method. Heavily regulated tributaries, such as the Rivière Gatineau and flow for the whole basin, show the winter period as one of weak recharge. This is the result of flow augmentation and does not represent true groundwater conditions.

Basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	E'												E
Gatineau							56	57	59				37
Lievre		35	31			34	55	51	53			32	28
Rouge	59	61	41			46	62	70	70	49	43	54	39
Madawaska						68	79	88	86	78	73		60
Kenojavis	75	76	74				68	73	72			68	47
Montreal							75	83	86	69	61		56
South Nation	78	78			63	89	93	95	95	85	74	73	60
Mattawa	58	60				59	78	79	74				40
Coulange	63	72	67				59	76	76	59	52	62	46
Blanche	80	84	79				76	85	85	61		67	54
Mississippi							83	89	88	84	79	72	61
Dumoine	56	66	66				63	73	79	62			50
Bonnechere		75					84	89	89	86	84	81	70
Rideau						81	89	92	90	82	76		67
Petawawa	67	71	65				61	79	86	79	73	69	58
Petite Nation	57	62					66	80	83	79	64	57	49
Whole Basin						55	69	75	76	62	56		51

Table 4-6: Annual evapotranspiration (E) and seasonal water flux (E') - precipitation minus discharge - both expressed as percent of precipitation. The state of ΔS is indicated by shading: white on black = +ve ΔS indicating groundwater recharge conditions; grey shading = $\Delta S \approx 0$, indicating periods of relative groundwater equilibrium (within 5% of annual evapotranspiration); normal text = -ve ΔS , indicating conditions of groundwater drawdown.

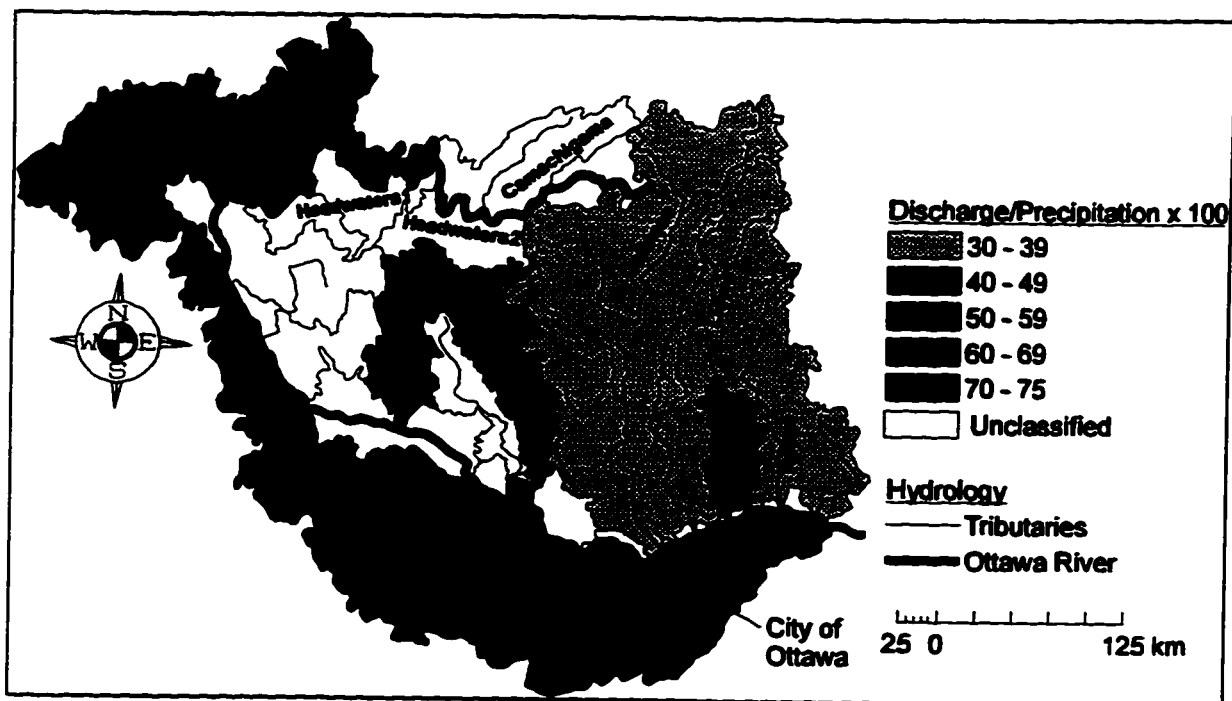


Figure 4-17: Percentage evapotranspiration per tributary basin.

Figure 4-17 is a map of annual evapotranspiration per tributary basin. The most obvious feature of the map is that higher evapotranspiration occurs in the southern portion of the basin than in the north. Further, there also seems to be an east west trend, with the higher evapotranspiration to the west. As indicated by the correlation coefficients in Table 4-7, these trends correlate strongly with climatic factors. The coldest, highest basins are located in the northeast where the lowest evapotranspiration occurs and the warmest, lowest ones in the southwest where the most evapotranspiration occurs. No significant correlation between open surface water and evapotranspiration exists, reinforcing the fact that most water losses to the atmosphere occur through vegetation. Correlations with physical basin characteristics, such as dominant tree species also exist but, as discussed in section 4.1.4c, these are the result of dependency. Speculatively, geological materials could play a significant role in the evapotranspirative flux. It seems logical that the soil-rich lowlands would be capable of supporting a larger biomass than the soil poor uplands, thus producing higher

evapotranspiration rates in the lowlands. Also, the soil poor, highly permeable (not porous) uplands probably do not retain water near the surface for utilization by plants for periods as long as those of the lowlands. Unfortunately, if this were true, the resulting trend would be difficult to discriminate from climate-induced trends.

Basin Characteristic	Annual Evapotranspiration
Average Altitude	-0.582
Average Latitude	-0.490
Average Longitude	-0.215
Abundance of Surface Water Area	-0.093
Annual Temperature	0.538

Table 4-7: Correlation coefficients of percentage annual evapotranspiration versus basin characteristics.

4.2.4 Evaporation, Transpiration and Interception

In nature, separating evapotranspiration into components of evaporation, transpiration, and interception is difficult. Typically these problems have been treated with extensive monitoring networks and sophisticated computer models.

Calculations of evaporation can be based on physical parameters such as humidity, solar radiation, temperature of the air and water, and wind velocities. They usually are based on Dalton's law:

$$E = C(p_w - p_a) \quad \text{Equation 4-9}$$

where E is the rate of evaporation; p_w is the vapour pressure in the film of air next to the water surface or, in other words, the maximum vapour pressure corresponding to the temperature of the water; p_a is the vapour pressure in the air above the water; and C is a coefficient dependent on barometric pressure, wind velocity and other variables. These formulae are good at predicting evaporation from evaporation pans but require extensive calibration and measurement networks to determine evaporation rates accurately from large

bodies of water and are of little use in calculating evaporated water over land. The determination of the appropriate wind velocity term is particularly difficult (Wisler and Brater, 1959). Other techniques for calculating evaporation have been based on energy balance and on humidity gradient. Again, both require extensive monitoring networks and area-specific calibrations.

Determination of regional transpiration rates are even more difficult, being based on similar parameters as those of evaporation calculations plus widely varying parameters like canopy structure, leaf display indexes, and canopy exchange processes. Section 4.1.4b discusses some of these efforts and Shuttleworth (1983) reviews many of the types of models used and their data requirements. Next we will examine alternative methods.

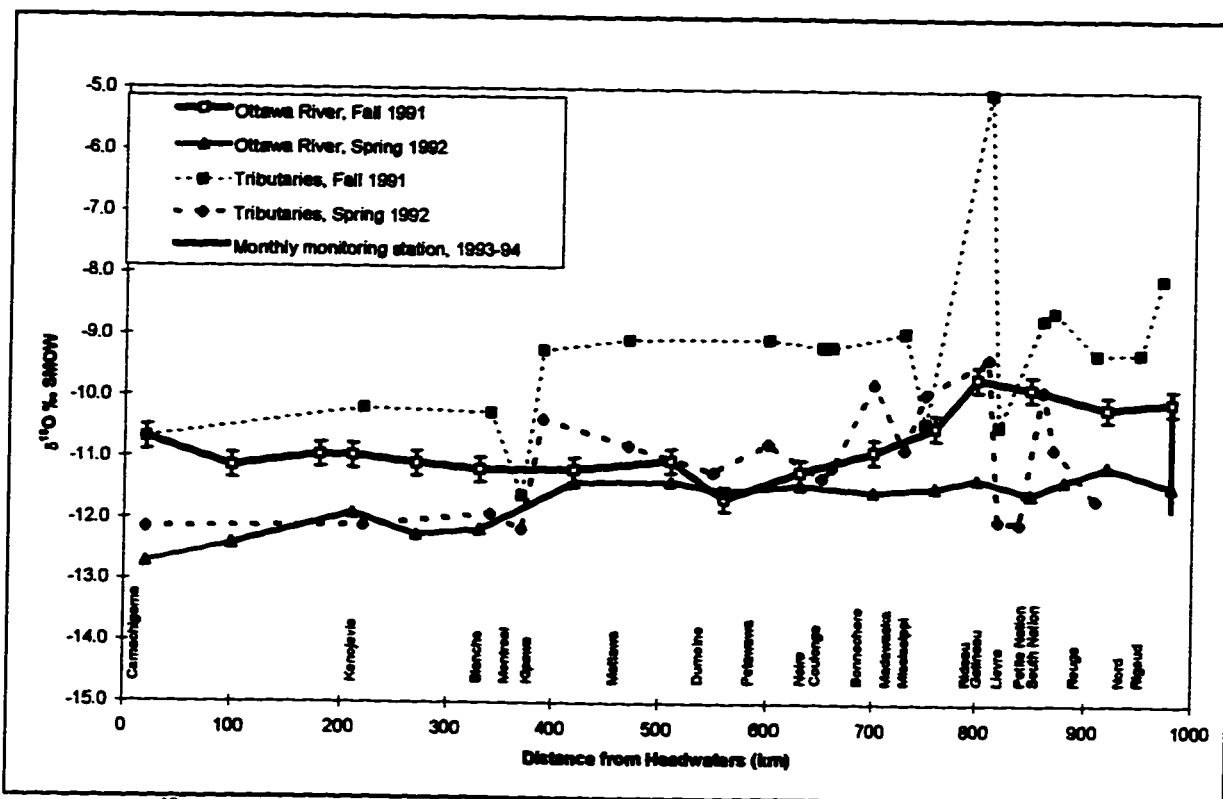


Figure 4-18: $\delta^{18}\text{O}_{\text{water}}$ versus distance downstream for the Ottawa River and its tributaries.

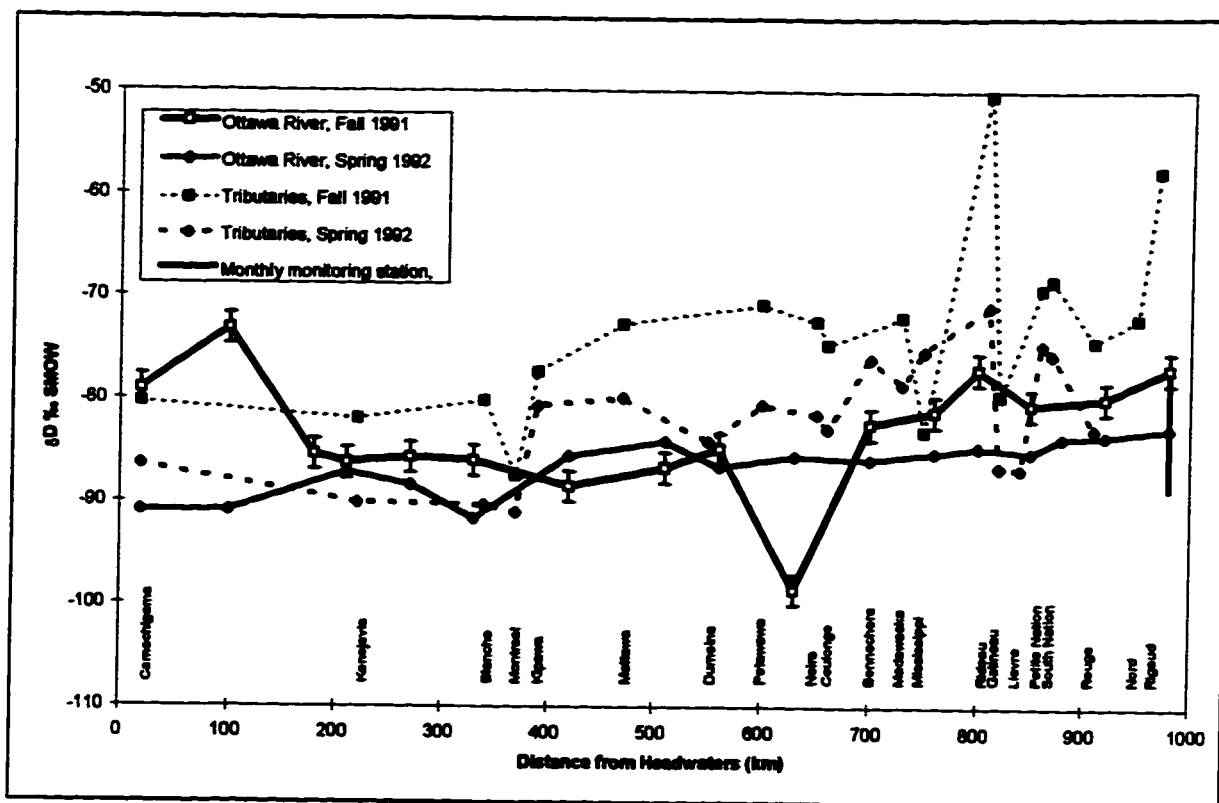


Figure 4-19: δD_{water} versus distance downstream for the Ottawa River and its tributaries.

4.2.4a Isotopic trends

The observed fluctuations of the $\delta^{18}\text{O}$ and δD composition of the water in the Ottawa River basin are shown in Figure 4-18 and Figure 4-19 and summarized in Table 4-8. All values are reported in ‰ relative to VSMOW.

Data Group and Date	$\delta^{18}\text{O}$ ‰ VSMOW	δD ‰ VSMOW
Max River, Fall 1991	-9.7	-73
Min River, Fall 1991	-11.7	-99*
Max Tributaries, Fall 1991	-5.1	-50
Min Tributaries, Fall 1991	-11.6	-87
Max River, Spring 1992	-11.1	-83
Min River, Spring 1992	-12.7	-92
Max Tributaries, Spring 1992	-9.4	-71
Min Tributaries, Spring 1992	-12.2	-91
Max Monitoring Station, 1993-94	-8.8	-74
Min Monitoring Station, 1993-94	-11.8	-99
Avg Monitoring Station, 1993-94	-10.7	-81
Discharge Weighted Average, Monitoring Station	-10.9	-82

Table 4-8: Maxima, minima, and averages of $\delta^{18}\text{O}$ and δD compositions of waters in the Ottawa River basin. * This value comes from an anomalous outlier.

During any one season, the isotopic minima and maxima occur in the upland and lowland tributaries such as the Montreal, Kenojevis and Gatineau versus the Rideau and South Nation Rivers. This pattern agrees with that predicted from a Rayleigh distillation where at higher latitudes and altitudes fresh waters become isotopically lighter (Dansgaard, 1964; Yurtsever, 1975; Hoefs, 1980). Values in the Ottawa River fall between the extremes and vary according to tributary input. In general, the headwaters of the river have relatively depleted values and the lower reaches have relatively enriched ones. The decrease in the isotopic values of the Ottawa River after its confluence with the isotopically light Rivière Gatineau and Lièvre, illustrates this process. The difference between the maximum and minimum of $\delta^{18}\text{O}$ in the river during any one season is about 2 ‰, and for the tributaries about 3 ‰. The extremely enriched value obtained for the Rideau River in the fall of 1991 is, as will be discussed next, the result of evaporation. The fact that no other tributaries show as strong an evaporative signal is somewhat mysterious.

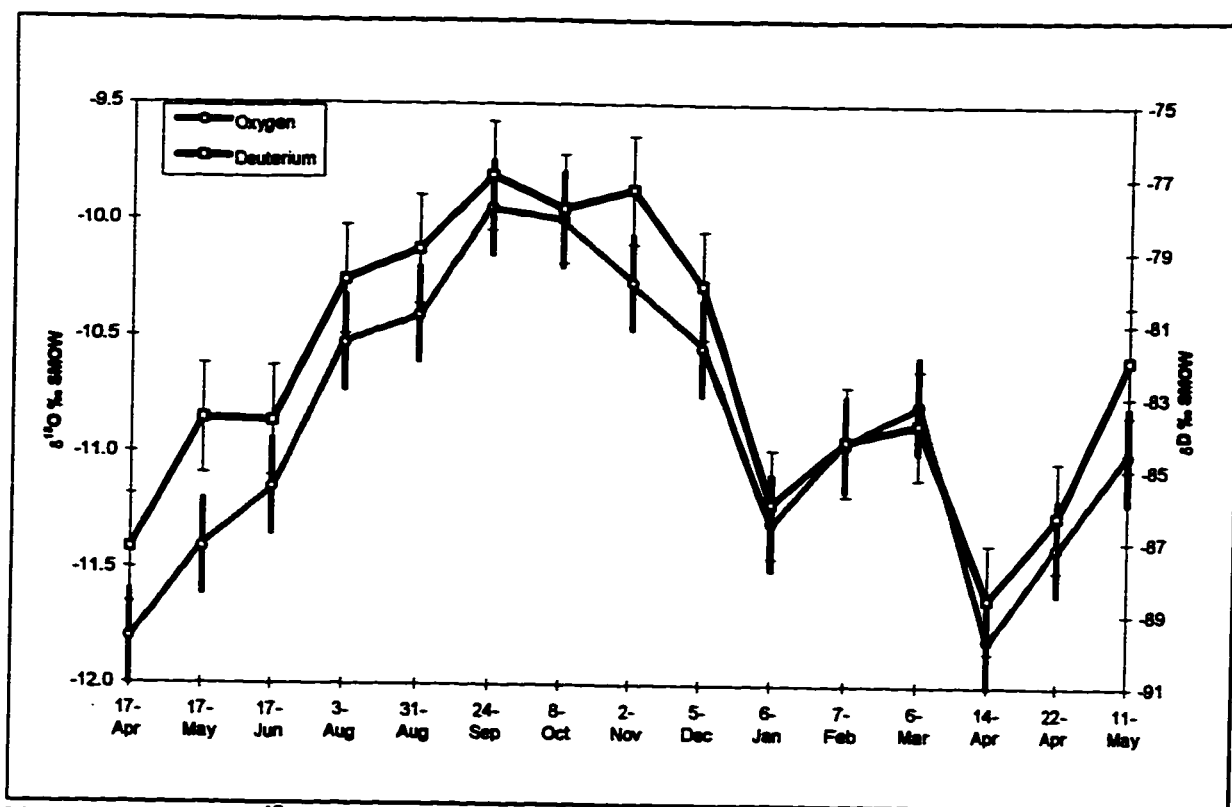


Figure 4-20: Monthly $\delta^{18}\text{O}$ and δD at the mouth of the Ottawa River.

Discharge from the mouth of the Ottawa River has a range of $\sim 2\text{‰}$ $\delta^{18}\text{O}$ over the year, attaining its minimum in April and its maximum in September (Figure 4-20). This is not surprising, as April is the time when the river contains the most snow melt which represents the most isotopically depleted water in the basin due to the fact that precipitation becomes isotopically lighter as air temperature decreases. The seasonal $\delta^{18}\text{O}$ -temperature coefficient in the Ottawa area is $0.31\text{‰}/^\circ\text{C}$ (Rozanski et al., 1992). Winter runoff is dominantly groundwater flow and augmented flow from hydro-electric reservoirs and so is isotopically heavier than the strong snow-melt signal of the spring. The flow augmentation signal is evident from January to March, as $\delta^{18}\text{O}$ actually becomes heavier over this period. September is a time when the river receives the most input from enriched sources - ground water, surface storage, and isotopically heavy summer precipitation - although direct inputs from summer

precipitation may be negligible due to evapotranspirative fluxes. The trends described for $\delta^{18}\text{O}$ are paralleled by δD , but at order of magnitude higher fractionations.

4.2.4b Isotopic composition of water within the Ottawa River basin

Precipitation at the city of Ottawa has an average isotopic composition of -10.89 ‰ and -74.2 ‰ for $\delta^{18}\text{O}$ and δD , respectively (Rozanski et al., 1992) but due to Rayleigh fractionation, precipitation in the colder upland regions of the basin will be much lighter. Maps of the isotopic composition of precipitation in Canada published by Fritz et al. (1987) illustrate this pattern. The weighted average isotopic composition of discharge at the mouth of the Ottawa River is calculated to be -10.9‰ but since the portions of the basin upland of Ottawa receive isotopically lighter precipitation, and these portions supply the majority of the runoff to the river, the value of -10.9‰ must be heavier than the average composition of precipitation for the basin. A crude verification of this assumption can be made using the linear relationship that Yurtsever (1975) established between average $\delta^{18}\text{O}$ of precipitation and average surface temperature for stations in Europe and Greenland:

$$\delta^{18}\text{O} = (0.521 \pm 0.014)T - 14.96 \pm 0.21 \quad \text{Equation 4-10}$$

Using an average basinal temperature of 3.5°C, calculated from daily temperature records over 60 years from 60 stations in a GIS, this calculation yields an average $\delta^{18}\text{O}$ of precipitation of -13.9 ‰, considerably lighter than the average $\delta^{18}\text{O}$ value at the mouth of the river. The difference between the value at the mouth and that of average precipitation can be accounted for by evaporation.

A more exact calculation of the average isotope composition of precipitation in the basin can be made. The relationship between $\delta^{18}\text{O}$ and δD for global precipitation can be approximated by the expression:

$$\delta\text{D} = 8\delta^{18}\text{O} + 10 \quad (\text{Craig, 1961}) \quad \text{Equation 4-11}$$

the so called World Meteoric Water Line (GMWL). However, Fritz et al. (1987) have determined that many regions in Canada have local meteoric water lines whose slope and intercept differ significantly from the GMWL probably due to different meteorological regimes and, in arid regions, to secondary fractionation processes. Clark et al. (1987) document some non-equilibrium reactions that can affect the isotopic composition of precipitation in some parts of the world, particularly in arid regions. However, under conditions found in humid river catchments, such as those in the Ottawa River basin, the final isotopic composition of precipitation is primarily controlled by two factors: (1) the initial isotopic composition of water vapour, and (2) Rayleigh distillation. Considering the first factor and the fact that Canada is inundated by air masses from the Arctic in the winter and from the Pacific, Atlantic and Gulf of Mexico in the summer, Fritz et al. (1987) also separated their observations into winter and summer meteoric water lines. The following three lines were determined for Ottawa:

$$\text{Winter:} \quad \delta\text{D} = 7.91\delta^{18}\text{O} + 11.03$$

$$\text{Summer:} \quad \delta\text{D} = 7.49\delta^{18}\text{O} + 4.76$$

$$\text{Year:} \quad \delta\text{D} = 7.63\delta^{18}\text{O} + 6.53$$

With the exception of several samples from the spring 1992 campaign, all data plot to the right of these lines, indicating that some evaporation has occurred since the initial

precipitation input (Figure 4-21). Considering that the samples from the mouth of the river represent the isotopic composition of runoff for the whole basin over the course of the year, the linear regression of these data produces an evaporation line for the basin:

$$\delta D = 6\delta^{18}O - 17$$

Equation 4-12

The intersection of this line with the LMWL yields the average isotopic composition of precipitation for the basin. It has a value of -14.5 ‰ and -103.8 ‰ for $\delta^{18}O$ and δD , respectively. Fortunately, the intersection of the evaporation line coincides with the intersection of the three LMWLs, eliminating the need for any seasonal considerations.

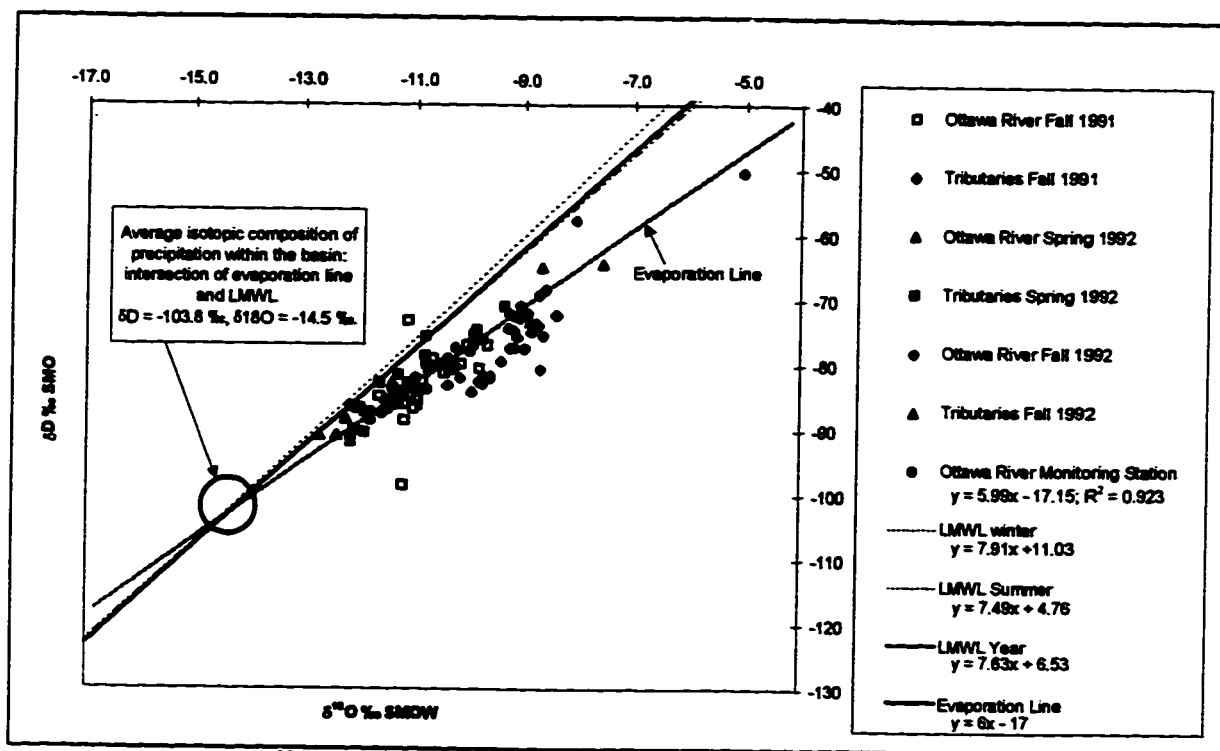


Figure 4-21: δD versus $\delta^{18}O$ for the Ottawa River and its tributaries, 1991-94.

4.2.4c Isotopic constraints on evaporation

Here, it is important to make clear the distinction between evaporation and transpiration, collectively called evapotranspiration. Transpiration is the evaporation of water to the atmosphere through the stoma of plants. Evaporation, in this case, will be considered

non-plant based evaporation. Transpiration is a non-fractionating process (Wershaw et al., 1966). Therefore the next calculation, based on isotopic fractionation, is for non-plant based evaporation only.

Gonfiantini (1986) used oxygen and hydrogen isotope systematics during evaporation to study water balances in lakes. The evaporative flux from the Ottawa River basin can be calculated based on Gonfiantini's equation:

$$x = \frac{(\delta_s - \delta_r)(1 - h + \Delta\epsilon)}{(\delta_s + 1)(\Delta\epsilon + \epsilon / \alpha) + h(\delta_a - \delta_s)} \quad \text{Equation 4-13}$$

where x is the percentage of evaporation; δ_s is the mean isotopic value of Ottawa River, assumed to be the weighted mean $\delta^{18}\text{O}$ and δD of discharge at the mouth; δ_r is the mean isotopic value of input (precipitation) to the basin, calculated above; δ_a is the mean $\delta^{18}\text{O}$ and δD of water vapour, estimated to be -13 and -113 ‰, respectively (Rozanski et al., 1992); h is the mean relative humidity estimated at 0.75 (Atmospheric Environment Services, 1990); α is the equilibrium fractionation factor at 15°C for $^{18}\text{O}/^{16}\text{O}$ and D/H , respectively; $\Delta\epsilon$ is the kinetic enrichment factor, evaluated here as $\Delta\epsilon^{18}\text{O}\text{‰} = 14.2(1-h)$, and $\Delta\epsilon\text{D}\text{‰} = 12.5(1-h)$, relationships typical for evaporation conditions most frequently encountered in nature (Gonfiantini, 1986); and $\epsilon = \alpha - 1$.

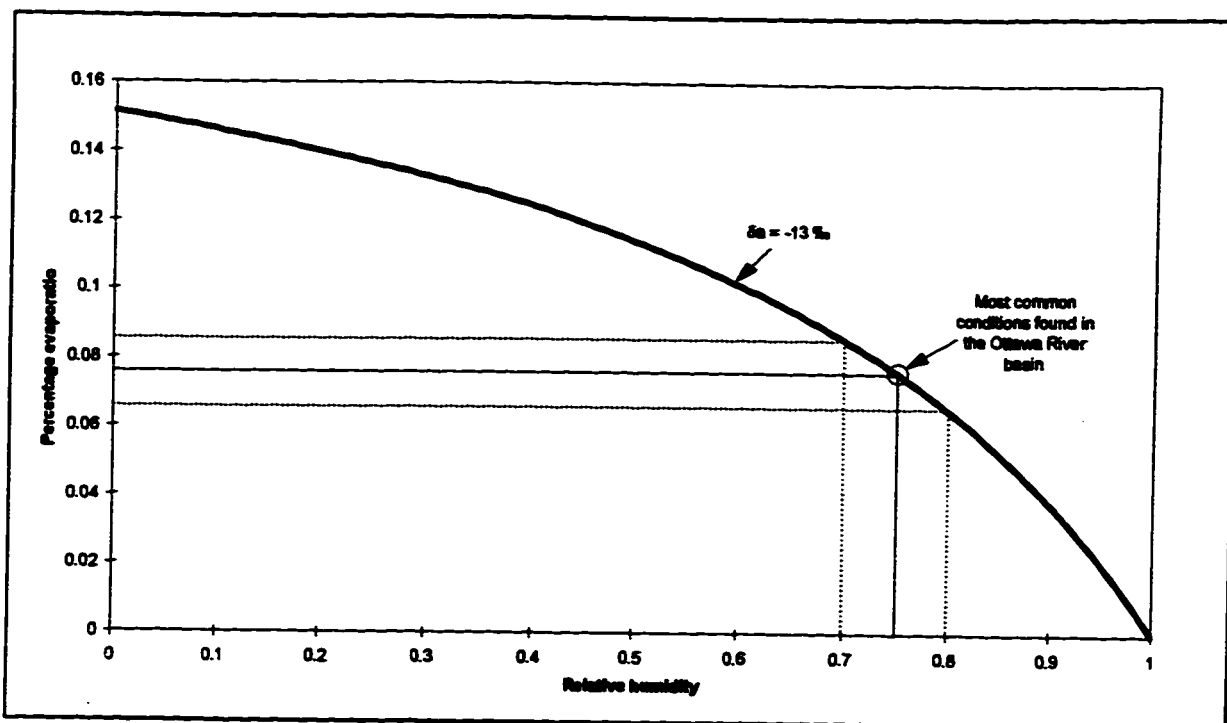


Figure 4-22: Percentage evaporation versus relative humidity and isotopic composition of the atmosphere in the Ottawa River basin.

This calculation shows that 8.1% of the total volume of water in the Ottawa River basin is evaporated during its residence time in the basin. This means that 8.1% of mean annual precipitation or 10.5 km^3 of water is evaporated from the basin annually. Since the mean residence time of water in the basin is likely greater than 1 year (it is unknown because the total volume of water in the basin is unknown), 10.5 km^3 represents a good estimate of average conditions, it is the integrated signal of several years. However, evaporation almost certainly varies from year to year with meteorological conditions. Figure 4-22 plots percentage evaporation against varying relative humidity in the basin. It can be seen that the evaporation rate is inversely proportional to relative humidity. For years with higher and lower than average relative humidities of 0.8 and 0.7, respectively, percentage evaporation would be lower and higher, at 7 and 9 %, respectively.

The effect of mean annual temperature fluctuations is more difficult to ascertain. This is due to the interdependency of δ_L , δ_s , ε and δ_a on temperature. During a warm year, the isotopic composition of the atmosphere will be less depleted and vice versa, altering the value of δ_a . The relationship between air temperature and isotope composition of ground level vapour is well documented (Rozanski et al., 1992). However, it is certain that under warmer or colder conditions the value of δ_L will also change in the same direction and, for small temperature differences, by about the same magnitude as δ_a . What is not known is the effect that changes in annual temperature will have on δ_s . Presumably, higher temperatures would cause an increase in evaporation rates and thus further enrich δ_s . However, this is certain only for potential evaporation and is dependent also on relative humidity. The complicated dynamics of interception, infiltration, vegetative effects, and groundwater flow make such a supposition more difficult for real evaporation. The large differences between potential evaporation and real evaporation rates for disparate areas is discussed by Riggs and Harvey (1990). Taking all this into account, it is presently not known whether the variations in mean annual temperature or those of relative humidity are a stronger control on evaporation in the Ottawa basin.

Under fixed annual isotope conditions, which is to say at fixed annual temperature conditions, equation 4-13 can be solved for percentage evaporation and relative humidity, consequently, the annual percentage evaporation in the Ottawa River basin can be estimated by following equation:

$$x = 0.158 - 0.034h - 0.143h^2 - 0.212h^3 - 0.193h^4$$

Equation 4-14

where x = percentage evaporation and h = relative humidity.

Notably, evaporation calculated from isotopes of water is based on the assumption that a residue is left after evaporation, that is the entire volume of water is not evaporated. For this reason, the above calculation represents evaporation from open water and soils only. It does not account for the evaporation of intercepted precipitation because this ephemeral reservoir evaporates to completion.

4.2.4d Biological water fluxes

Transpiration, which is water evaporated to the atmosphere through the stoma of plants, can be defined as:

$$t = E - e$$

Equation 4-15

where t is transpiration; E is evapotranspiration; and e is evaporation. Since evapotranspiration and evaporation have been determined previously, the calculation of transpiration is a simple matter of subtraction. This yields an annual transpiration rate of 43% of annual precipitation or 55.9 km^3 . Unfortunately, these calculations do not discriminate water flux to the atmosphere caused by transpiration from that caused by interception. For this reason and since interception is almost exclusively caused by plants, it would be more accurate to say, biological water fluxes equal 43% of annual precipitation.

4.3 WATER BALANCE MODEL

It has been shown above that the water balance in the Ottawa River results from a combination of seasonal and spatial climatic changes, physical basin characteristics such as geology and related water storage capacity, vegetation cover, and possibly landuse. Figure 4-23 summarizes the results of these interactions. The magnitude of precipitation, discharge, groundwater flux, and temperature through time has been determined from observations. The

magnitude of evapotranspirative fluxes through time was estimated from temperature and leaf display index (Soegaard and Boegh, 1995).

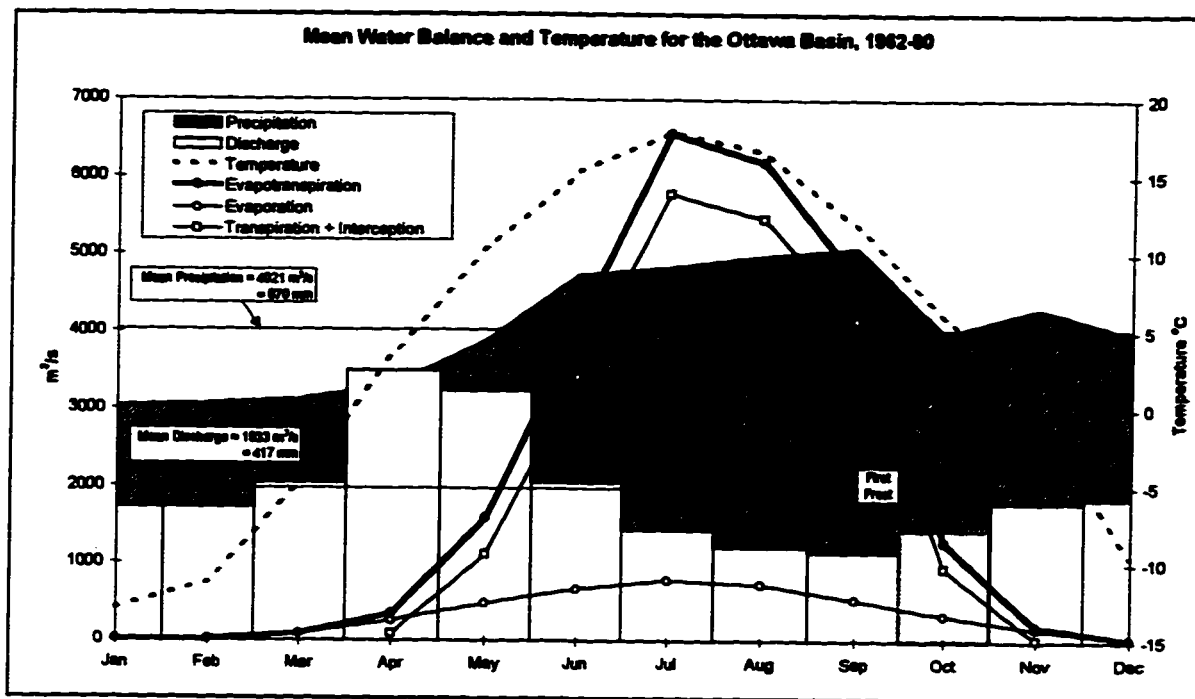


Figure 4-23: Monthly water flux and temperature for the Ottawa River basin.

Solar radiation is the driving force of the system. Manifestations of fluctuations in solar radiation are evident in all the variables shown in figure 4-23. Basinal temperature is lowest in January, with an average value of -13°C and peaks in July at 17°C , lagging behind total solar radiation by about one month. Precipitation also follows this pattern, with the maximum precipitation occurring in the summer months when warm moist air masses originating from the south deliver more moisture to the basin than the cold dry arctic air masses in the winter. Evaporation rates follow the temperature curve, bottoming out in January and peaking in July. Evapotranspiration is equal to evaporation in the winter months until rising temperatures begin the growing season in late April. From May to October evapotranspiration is dominated by its transpiration component, peaking in July with temperature and then abruptly terminating in October with the frost. Interestingly, discharge

has a more or less inverse relationship with precipitation. Stored precipitation in the form of snow is released in the spring by rising temperatures and then falls to a minimum in September when precipitation is highest. This is due to evapotranspirative drawdown. The amount of water lost to evapotranspiration (63 km^3) is roughly equal to that precipitated (62 km^3) during the growing season and as a consequence, no water is added to the ground water system during this time. This also explains why the rise in discharge in the fall occurs when precipitation decreases. Sometime in October, transpiration is abruptly ended by frost allowing groundwater recharge to commence. This has been seen in small streams. Riggs and Harvey (1990) describe an example where a small stream in Virginia ceased to flow after a month without rain. After temperature decreases in the fall, flow commenced before any rainfall occurred. A combination of frontal precipitation, lack of transpiration, and unfrozen soil causes the fall rise for most of the tributaries to peak in November. After November, freezing prevents infiltration and the period of winter drawdown begins. This is not the case for the Ottawa River because of flow augmentation practices by hydro-electric reservoir operators. Augmented flows maintain winter flows above normal levels.

Physiography plays a major role in this cycle. Cooler upland regions release their spring snowmelt more slowly and at later times due to climatic, geological, and surface morphological conditions. Evapotranspirative losses are lowest for these regions, averaging 40% of precipitation. In contrast, the warm lowlands release their spring snowmelt rapidly and earlier in the season. Evapotranspiration is highest for these basins, averaging 65% of precipitation. This is due primarily to the climate but may also be augmented by the presence of rich soils and low infiltration rates in the lowlands, allowing vegetation to consume a

greater portion of water than in the soil-poor uplands which support a smaller biomass and move water more rapidly away from the near surface, reducing the ability of vegetation to consume it.

The only unquestionably human impact on the water budget of the basin is that caused by flow regulation from artificial reservoirs. This impact can be dramatic, particularly in the vicinity of the reservoirs, where the natural seasonal rhythm of discharge is completely reversed causing low water stand to occur during spring thaw and high water stand in winter, normally the period of lowest flow. Further downstream, after significant inputs from unregulated areas of the basin, the seasonality of flow begins to recover. This human signal overprints natural ones throughout the basin, but it is strongest in the upland regions where reservoirs are large. It is possible that land use practices such as crop tilling and forest harvesting influence the nature of flow in the basin but any such influences are secondary to natural processes.

Water balance cycles and the factors that control them bear a heavy influence on the chemistry of basinal waters. This will be investigated in the next chapter.

5 BIOGEOCHEMISTRY

The previous chapter describes how the interaction of water with climate, geology, vegetation, and human interests is manifest in the temporal and spatial aspects of the water cycle in the Ottawa River basin. With these factors in mind the chemistry of the river and its controls are examined.

All river water begins in the atmosphere in the form of precipitation. Precipitation is not pure water but contains a dilute mixture of dissolved substances. Close to the coasts, ocean spray provides considerable amounts of Cl and Na to precipitation. Further inland Cl and Na are superseded by Ca, Mg, K, SO_4 , NO_3 and NH_4 , which are inputs from terrestrial dust, terrestrial vegetation, and pollution (particularly SO_4) (Berner and Berner, 1987). Before flowing back to the sea in rivers, the dissolved load of precipitation is altered by three primary mechanisms: 1) evapotranspiration outgasses pure water to the atmosphere concentrating the residue; 2) the dissolution of minerals in soils and ground water systems increases the solute load; and 3) interactions with the biosphere add soluble organic compounds and remove some solutes such as potassium and nitrogen compounds (Drever, 1988). As will be seen, the importance of each mechanism differs for each ion in accord with the physiochemical characteristics of the drainage basin.

5.1 ATMOSPHERIC BUDGET

Table 5-1a compares the estimated average composition of precipitation falling in the Ottawa River basin with the average composition of the Ottawa River and its tributaries for the dominant chemical species found in precipitation. Table 5-1b lists the percentage of the

riverine ion budget that can be accounted for by taking into account concentration increases caused by evapotranspiration (calculated in chapter 4) using the following equation:

$$c = \frac{[p]/(1-E)}{[r]} \quad \text{Equation 5-1}$$

where c is the percentage contribution from precipitation; $[p]$ is the ionic molality of precipitation; E is the percentage evapotranspiration; and $[r]$ is the ionic molality of river water.

a. composition	Na ⁺ μmol/l	K ⁺	Mg ²⁺	Ca ²⁺	DIC*	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	NH ₄ ⁺	pH
Precipitation	8.3	3.3	4.6	11	13	8.9	46	1.8	21	6.8
<i>Ottawa River</i>	<i>139</i>	<i>20</i>	<i>95</i>	<i>253</i>	<i>680</i>	<i>117</i>	<i>101</i>	<i>5.9</i>	<i>4.7</i>	<i>7.0</i>
Kipawa	45	21	31	68	53	22	100	1.6	1.4	6.2
Mattawa River			71		191	65			4.3	7.1
Petawawa River	105	19	63	185	224	46	106	1.6	0.9	7.4
Rivière Coulonge	66	23	45	122	189	87	75	2.5	2.6	6.9
Bonnechere River	160	41	253	585	1213	158	138	1.7	2.7	7.8
Madawaska River			141		814	127			0.9	7.7
Mississippi River	132	37	281	803	1891	167	142	1.5	2.2	8.0
Rideau River	225	41	521	969	2255	439	175	2.4	3.4	7.9
Rivière Gatineau	57	18	46	145	229	39	66	2.9	1.6	7.0
Rivière Du Lievre	57	18	39	149	247	38	65	4.2	1.7	7.0
Rivière Petite Nation	116	34	76	245	467	91	112	4.8	1.8	7.3
South Nation River	706	86	522	1173	2713	868	312	5.1	6.5	7.9
Rivière Rouge	138	22	62	169	196	106	83	5.2	1.7	7.0
Du Nord	563	25	106	280	1122	612	124	10	5.8	7.3
Rigaud	718	77			2632	386	396	21	3.9	8.0

b. proportion contributed from rainfall - [residue]/[river]	% evapotranspiration									
<i>Ottawa River</i>	<i>0.12</i>	<i>0.34</i>	<i>0.10</i>	<i>0.09</i>	<i>0.0</i>	<i>0.1</i>	<i>0.91</i>	<i>0.61</i>	<i>9.20</i>	<i>51</i>
Kipawa	0.33	0.29	0.26	0.29	0.4	0.7	0.80	1.96	27.65	44
Mattawa River			0.11		0.1	0.2			8.17	40
Petawawa River	0.19	0.41	0.17	0.14	0.1	0.5	1.01	2.69	52.87	58
Rivière Coulonge	0.23	0.27	0.19	0.17	0.1	0.2	1.10	1.31	15.11	46
Bonnechere River	0.17	0.27	0.06	0.06	0.0	0.2	1.09	3.54	25.94	70
Madawaska River			0.08		0.0	0.1			55.44	60
Mississippi River	0.16	0.23	0.04	0.04	0.0	0.1	0.82	3.15	24.64	61
Rideau River	0.11	0.24	0.03	0.03	0.0	0.0	0.78	2.22	18.50	67
Rivière Gatineau	0.23	0.30	0.16	0.12	0.0	0.4	1.08	0.98	20.52	37
Rivière Du Lievre	0.20	0.25	0.16	0.10	0.0	0.3	0.96	0.59	17.42	28
Rivière Petite Nation	0.14	0.19	0.12	0.09	0.0	0.2	0.78	0.72	22.55	49
South Nation River	0.03	0.10	0.02	0.02	0.0	0.0	0.36	0.86	8.07	60
Rivière Rouge	0.10	0.25	0.12	0.11	0.1	0.1	0.89	0.56	20.69	39
Du Nord	0.03	0.25	0.08	0.08	0.0	0.0	0.70	0.33	6.93	48
Rigaud	0.03	0.11			0.0	0.0	0.28	0.21	13.57	60

Table 5-1: a. Annual average composition of precipitation (bolded) (Schindler et al., 1976; Barrie and Hales, 1984), Ottawa River (italicized) and tributary waters (calculated from Environment Canada, 1993); *DIC in rain water is calculated below in section 5.3.1. For more details on the Environment Canada data, see appendix C, tables 1 & 2. b. Proportion of riverine ion concentration contributed by precipitation.

Evidently, contributions from precipitation can account for very minor proportions of the riverine ion budget for some species, such as Ca^{2+} , while for others, such as SO_4^{2-} , it plays a dominant role. For non-conservative species, like NH_4^+ and NO_3^- , the calculations are less meaningful. All this will be elaborated on in the sections discussing the individual species.

5.2 CHLORIDE AND SODIUM

The origin and behavior of chloride in river water is perhaps the simplest to understand of all the ions. It reacts very little with other ions, does not form complexes, is not greatly adsorbed on mineral surfaces, and does not participate in biogeochemical cycling (Berner and Berner, 1996).

5.2.1 Sources

Its natural source is almost exclusively seasalt (NaCl), either transported inland by atmospheric aerosols, released by the dissolution of halite deposits (evaporated seawater) or by leaching of trapped seawater in shales (Lahermo et al., 1994). Each molecule of Cl^- from seasalt is accompanied by one of Na^+ and discussion of the behavior of Na^+ is included therefore in this section. Road salting and industrial uses are the primary anthropogenic sources of Cl^- . Howard et al. (1993) describe the acute situation in metropolitan Toronto where it is predicted that massive applications of NaCl for road de-icing will lead to steady state base flow concentrations of 400 mg/l, well above the standards for aquatic life and drinking water. Road salting in the Ottawa River basin is just as intense and the season is 2-4 weeks longer, but the smaller road network keeps the total application of salt below Toronto levels. As well, the discharge of the Ottawa River and of its major tributaries are roughly an

order of magnitude greater than that of the streams draining the greater Toronto area. This reduces the impact of locally high baseflow Cl^- concentrations due to greater dilution capacity.

A smaller but significant anthropogenic source of Cl^- is municipal water and waste treatment operations where chlorine is used for disinfection and oxidative removal of Fe^{2+} , Mn^{2+} , S^{2-} , and organic compounds. The general reaction for chlorination is (Stumm and Morgan, 1996 p. 699):



This is the only major source of Cl^- to rivers that is not accompanied by equivalent Na^+ , although cation exchange in clays can consume Na^+ decreasing the Na/Cl values.

Figures 5-1 and 5-2 plot Cl^- versus Na^+ from this study and for corroboration, data covering a much greater period of time and all seasons from the Envirodat database (Environment Canada, 1993). All samples plot close to the molar ratio of Na:Cl (1:1) indicating that the dissolution of NaCl (anthropogenic or natural) is the primary source of Cl^- in the basin. Table 5-1 shows that Cl^- contributed from precipitation averages 17% for the Ottawa River basin but can be as high as 79% for the dilute Rivière Kipawa and as low as 3% for rivers like the South Nation and the Rivière du Nord. The latter receive anthropogenic inputs of Cl^- from road salting, agriculture, industry, and municipal sewage and water treatment (Merriman and McCrea, 1982) as well as natural inputs of Cl^- from trapped pore water in the Champlain Sea clays (Torrance, 1988) and Paleozoic shales (Hofmann, 1972). It is difficult to resolve the proportions of anthropogenic versus natural Cl^- for river basins that have both non-cyclic natural salt and anthropogenic sources but the estimates discussed below suggest that the majority of Cl^- is of natural origin.

5.2.2 Na⁺ Excess

Deviations from the NaCl line in Figure 5-1 and Figure 5-2 can be caused by silicate weathering, industrial and municipal Cl⁻ discharge, cationic exchanges of Na⁺ in clays, and by analytical error. Deviations with Na/Cl greater than 1 (Na⁺ excess) are likely caused by the weathering of Na-silicate minerals, such as albite that release Na⁺ into solution. Deviations of this type would be expected for the dilute shield streams which are dominated by silicate geology and, indeed, most of these streams do have Na⁺ excesses (generally represented by samples below 100 $\mu\text{mol/l}$ on Figures 5-1 and 5-2). More salinized lowland tributaries, which drain Paleozoic and Quaternary sediments, generally plot closer to a 1:1 ratio. Nonetheless, the weathering of the Champlain Sea clays, which contain large quantities of relatively fresh and fine-grained silicate materials (Gadd, 1986; Torrance, 1988), can release Na⁺ pushing the Na/Cl values higher than one for these streams as well.

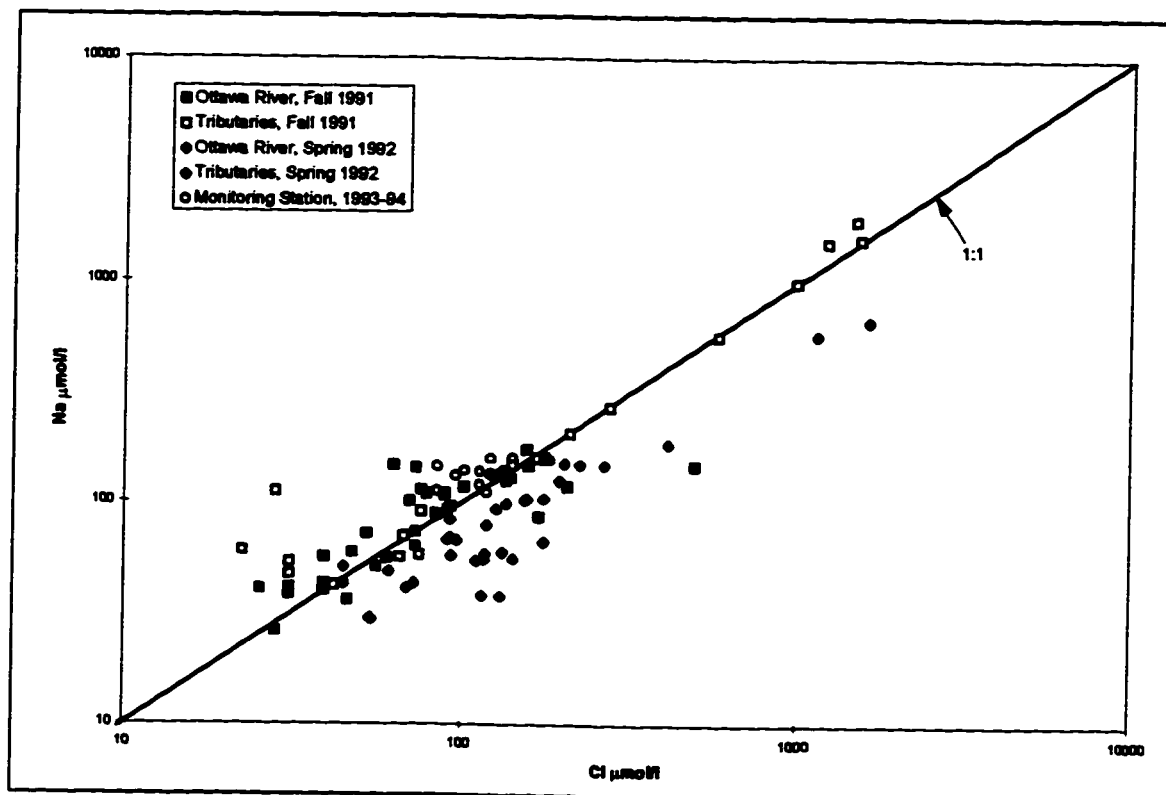


Figure 5-1: Na^+ versus Cl^- for the Ottawa River and its tributaries, data from this study.

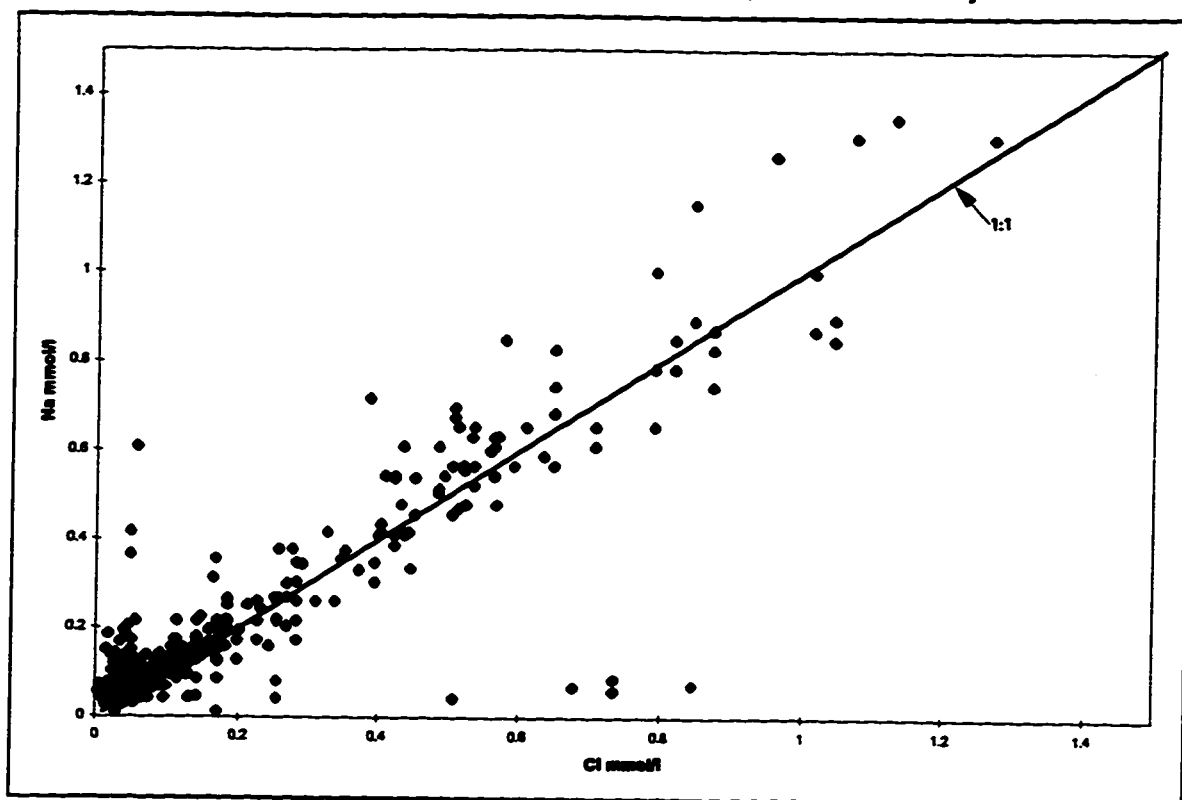


Figure 5-2: Na^+ versus Cl^- for the Ottawa River and its tributaries, data from Environment Canada (1993).

5.2.3 Temporal Distribution and Cl^- excess

Mysteriously, many samples from the spring of 1992 generally have Na/Cl less than 1. This same seasonal feature occurs in the Environment Canada (1993) data but not as strongly. Ingri and Widerlund (1994) have proposed that Na^+ is incorporated in non-detrital Fe in the spring and winter in Swedish rivers. They claim that up to 40% of the suspended Na^+ concentration was found in non-detrital form, suggesting that it had been scavenged from the dissolved load. Such a scenario, which would produce a Cl^- excess, is plausible for the Ottawa River which shares many climatic and geologic characteristics with the rivers in the Swedish study. Strengthening this hypothesis is the fact that Fe concentrations (probably in colloidal and hydroidal form) in the Ottawa River basin are generally elevated in the winter and spring

(appendix A and C). Seasonal fluctuations in the non-detrital Fe concentration provide a mechanism for the seasonal scavenging of Na^+ , producing the observed seasonal Cl^- excesses.

Although Ingri and Widerlund's (1994) model seems to fit well for the Ottawa basin data, further analysis suggests an alternative, perhaps more favourable model. Spring Cl^- enrichments can be more effectively explained by the retarded transport of Na^+ through ground water and soil systems due to ion exchange such that, in the spring when hydraulic gradients are rapidly increased, atmospheric and anthropogenic Cl^- which has been collecting in snow and ground water over the winter, is flushed from the system more rapidly than Na^+ . This theory is supported by the fact that, at the mouth of the Ottawa River over time, Cl^- has roughly twice the variance of Na^+ suggesting that Cl^- response to environmental change is more rapid than that of Na^+ . This is evident in Figure 5-3, which shows the behavior of Cl^- and Na^+ over time at the mouth of the Ottawa River. Clearly, the two ions do not behave correlatively as would be expected for conservative behavior from a dominantly salt source. Both the impact of the additional source of Na^+ from silicate weathering and the non-conservative behavior of Na^+ are evident in the plot and can be related to seasonal hydrological and anthropogenic events. During early winter when the application of road salt has begun and before infiltration of water to the ground water system is locked out by freezing and during spring thaw when anthropogenic salt that has been accumulating in snow and aquifers over the winter is released, a salt signal ($\text{Na}/\text{Cl} \approx 1$) is dominant. During this time, cationic exchange retards the release of Na^+ such that Cl^- concentrations exceed those of Na^+ , despite the fact that the long term flux of Na^+ is greater than Cl^- due to Na^+ additions from silicate weathering. During the summer when low water stand occurs, much of the winter salt

has been flushed from the system (Howard et al. (1993) claim that 45% is flushed annually and the remainder is incorporated in long term baseflow), a greater proportion of water is supplied from the upland silicate tributaries due to their greater water storage capacity and some flow augmentation practices (see chapter 4), and weathering rates are enhanced by high summer temperatures. These factors produce a silicate weathering signal which is characterized by intermediate concentrations of Na^+ and low concentrations of Cl^- . Concentrations of Na^+ exceed those of Cl^- not only because of silicate weathering but also due to buffering by retardation which prevents Na^+ from salt inputs from being flushed as rapidly as Cl^- .

A similar cycle of lesser magnitude occurs in deep winter. During this time, a greater relative proportion of Ottawa River water comes from Na-enriched upland sources (silicate basins) due to greater baseflow and flow augmentation practices, and NaCl input from salt is prevented by the cessation of infiltration by freezing, together causing Na^+ concentrations to exceed those of Cl^- .

Figure 5-4 is similar to Figure 5-3 but the data comes from Environment Canada and is averaged over 10 years. The general trends and concentrations agree well with the data from this study and the above described cycle is equally valid. However, averaging smoothes the curves to such a degree that they never cross over. For individual samples, cross-overs, where Cl^- exceeds Na^+ during the spring and fall, are common.

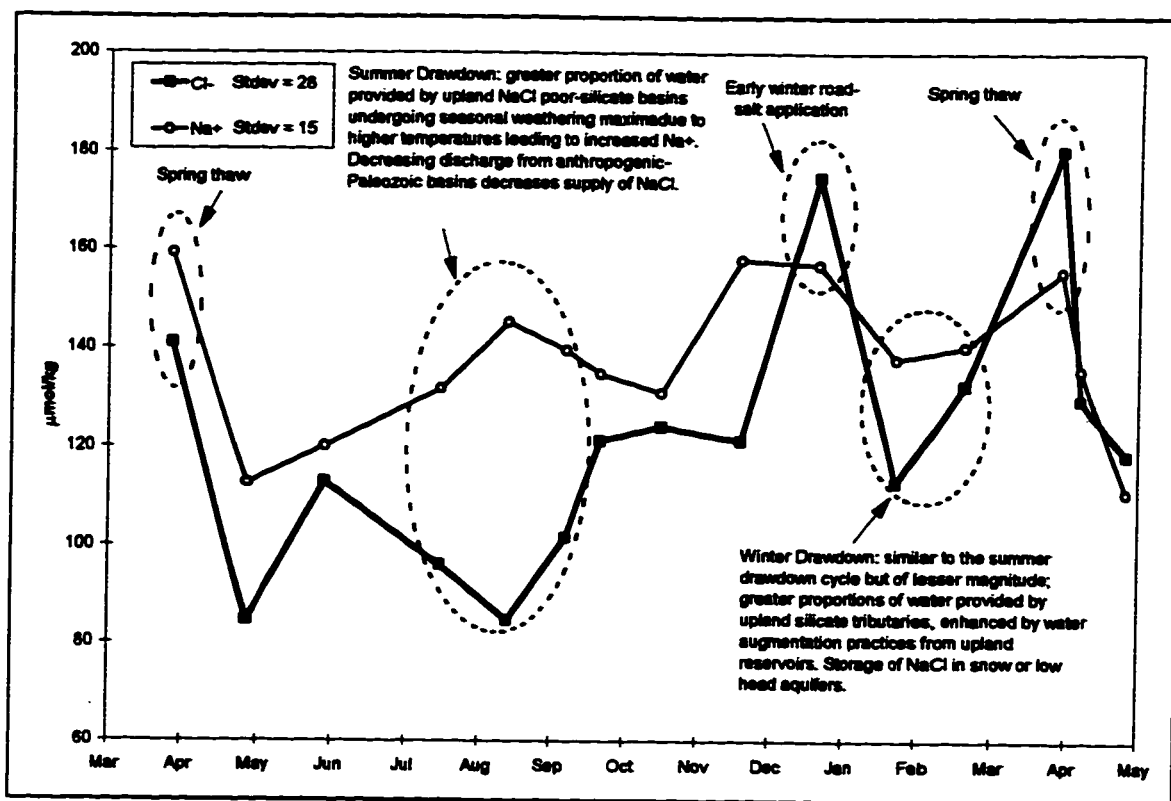


Figure 5-3: Monthly Cl^- and Na^+ concentrations at the mouth of the Ottawa River; data from this study 1993-94.

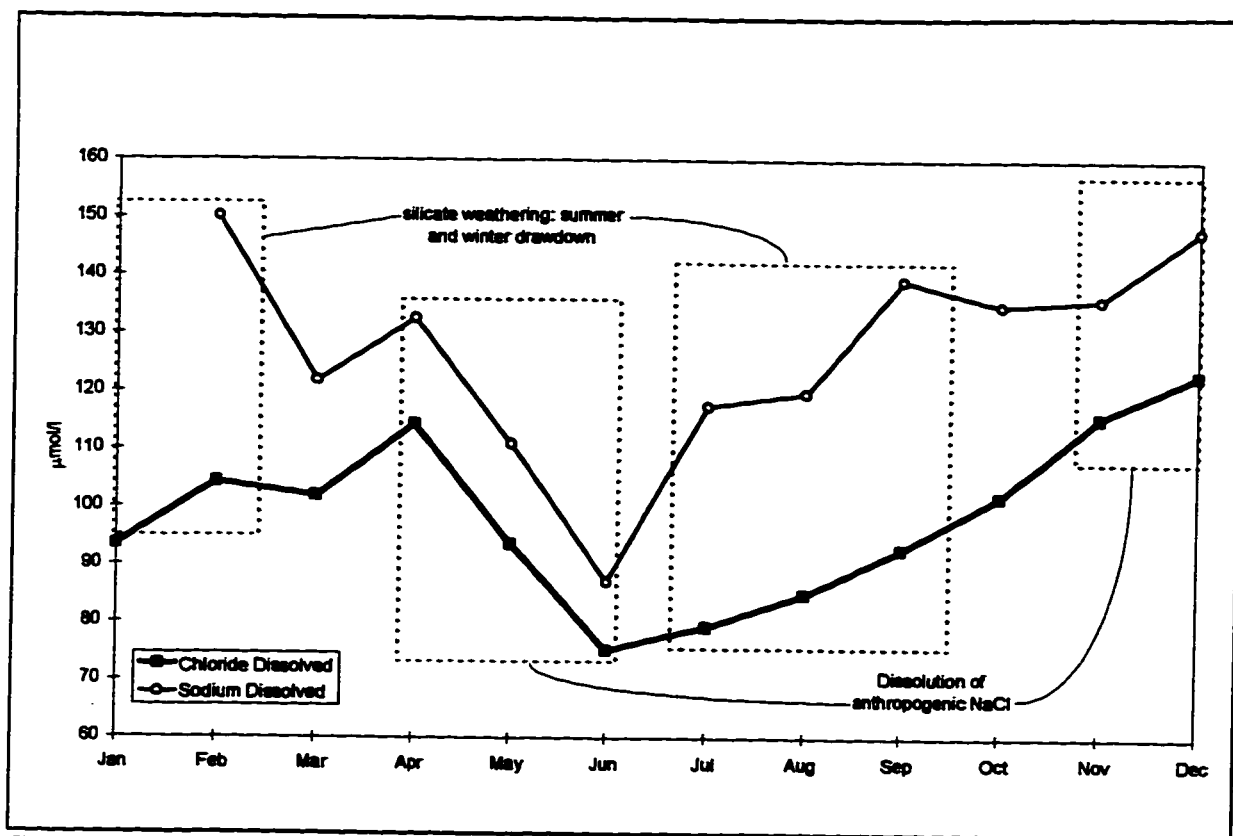


Figure 5-4: Average monthly Na⁺ and Cl⁻ concentrations for the decade 1978-1988; data calculated from Environment Canada (1993).

The Rivière Kipawa and the South Nation River are examples of the two endmembers controlling the Cl⁻ and Na⁺ concentrations of the Ottawa River. The Rivière Kipawa receives the majority (79%) of its small Cl⁻ flux from atmospheric deposition. Its Na⁺ flux is dominated by silicate weathering and is double the flux of Cl⁻. The South Nation River receives only 3% of its substantial Cl⁻ flux from the atmosphere and its Na⁺ flux from silicate weathering is swamped by the flux from salt. Consequently, Cl⁻ and Na⁺ closely mirror each other, but Na⁺ is moderately retarded. Figures 5-5 and 5-6 illustrate these features.

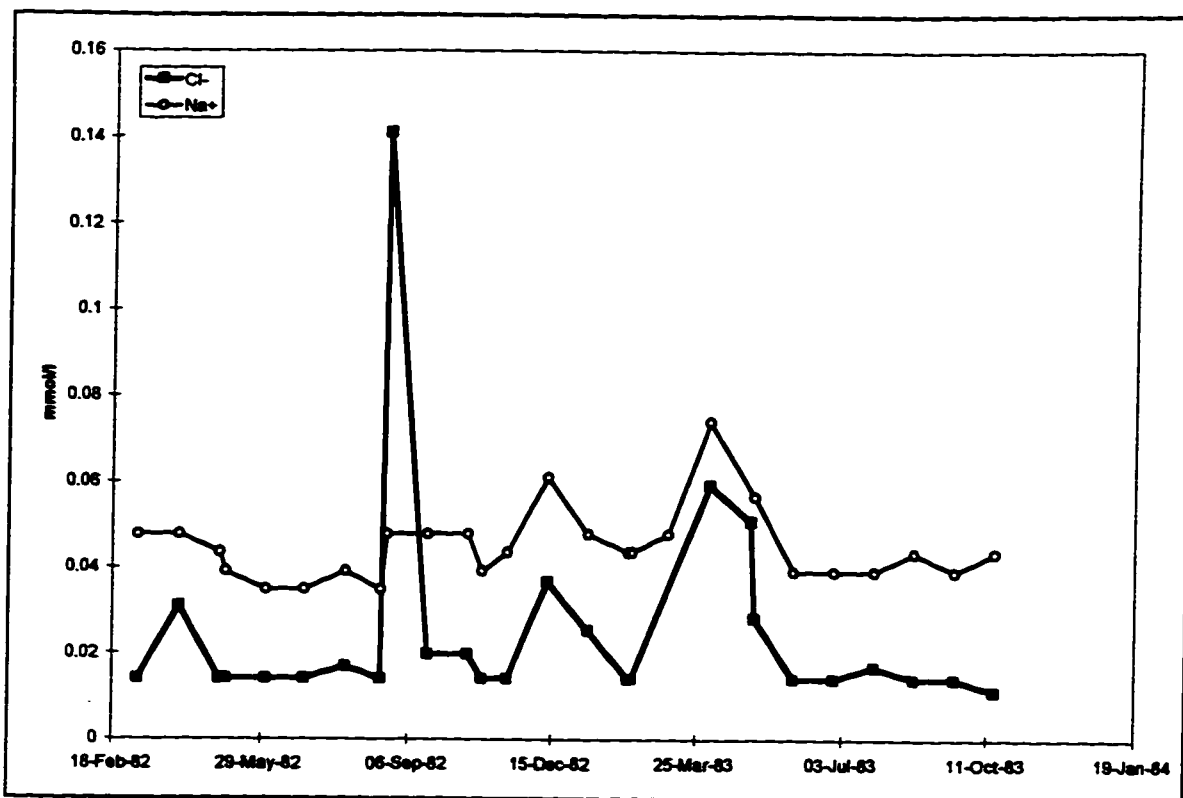


Figure 5-5: Na⁺ and Cl⁻ concentrations versus time for the Rivière Kipawa; data from Environment Canada (1993).

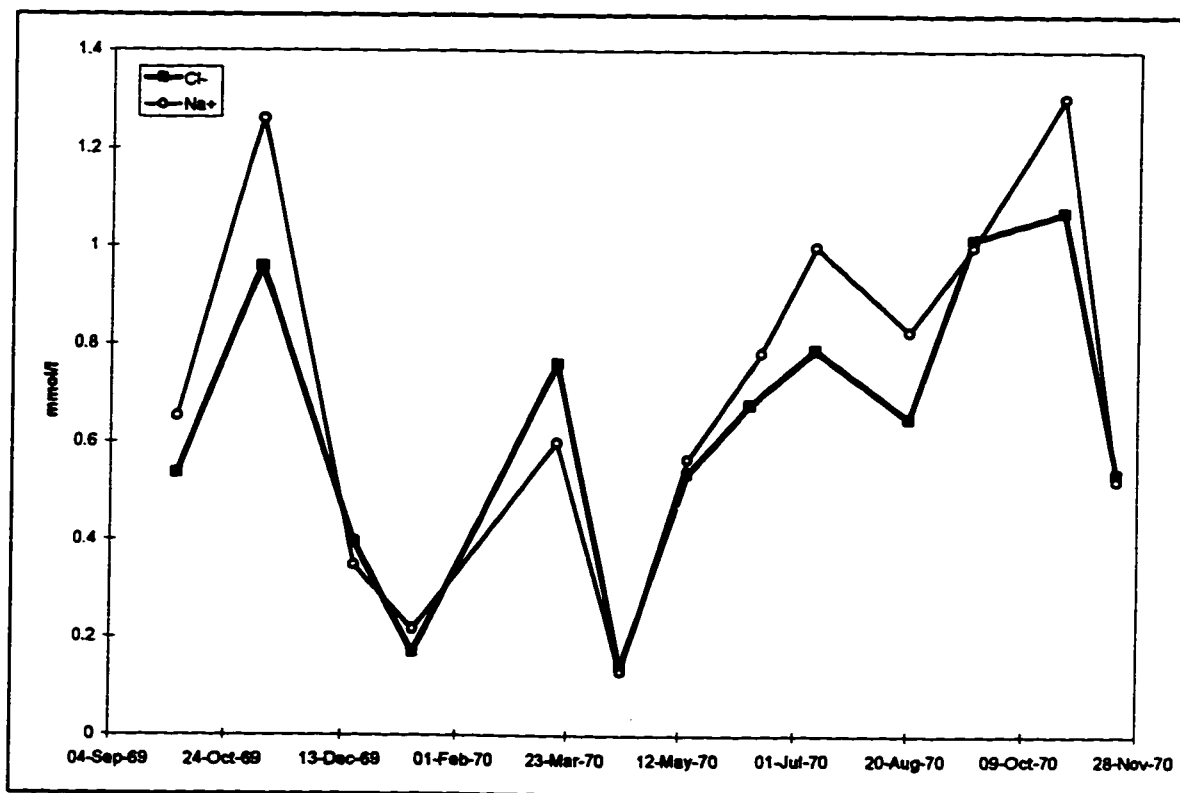


Figure 5-6: Na⁺ and Cl⁻ concentrations versus time for the South Nation River; data from Environment Canada (1993).

One other possible natural source for Cl^- in surface waters of the Ottawa River basin are Ca-Na-Cl brines found at depth in almost all areas of the Canadian Shield (Frape and Fritz, 1987). The deep brines are usually associated with subhorizontal shear zones at average depths of 1000-2000m, and have very high concentrations of TDS ($>250\text{g/l}$). It is thought that these brines are not active hydrogeologically, but at lesser depths ($\sim 1000\text{m}$) vertical shear zones contain brackish waters ($\text{TDS} < 10000 \text{ mg/l}$ due to mixing of brine and meteoric waters) and they are connected to the surface. Small discharge or exchange from these waters may explain the presence of Cl^- in watersheds, such as the Kipawa, that have greater concentrations of Cl^- than can be accounted for by atmospheric input despite the absence of any obvious geological or anthropogenic sources. An alternative explanation is that all the Cl^- in the Kipawa basin is atmospheric in origin and that this source has been underestimated.

5.2.4 Spatial Distribution

The primary control on chloride concentrations varies with population base and lithology. Figure 5-7 shows the downstream trend of Cl^- concentrations for the Ottawa River, and the mouths of the tributaries, for the spring and fall. Input from precipitation is the dominant source where anthropogenic inputs and Paleozoic sediments are absent, reaching as much as 79, 51, and 40 % of the load in the upland Kipawa, Petawawa and Gatineau basins, respectively. The upper 300-400km of the Ottawa River also fall into this category. Pore water in Champlain sea sediments (Torrance, 1988) and possibly the Ordovician shales, the March and Oxford sequences contain some halite casts (Hofmann, 1972), represent the most probable natural sources of chloride in the basin, excluding deep brines. These sources are located primarily in the lowlands where Cl^- concentrations reach their maxima. Yet, the bulk

of the increase in Cl^- concentrations occurs already in the middle sections of the Ottawa River, suggesting that anthropogenic input also plays a role in controlling dissolved chloride in the basin. This is borne out by the fact that chloride concentrations correlate almost perfectly with population, but not with geology. For example, the Kenojevis River, that drains a catchment with no Paleozoic sediments or other large natural source of chloride, but does contain a large population centred around Rouyn-Noranda, an industrial complex, has relatively high chloride concentrations.

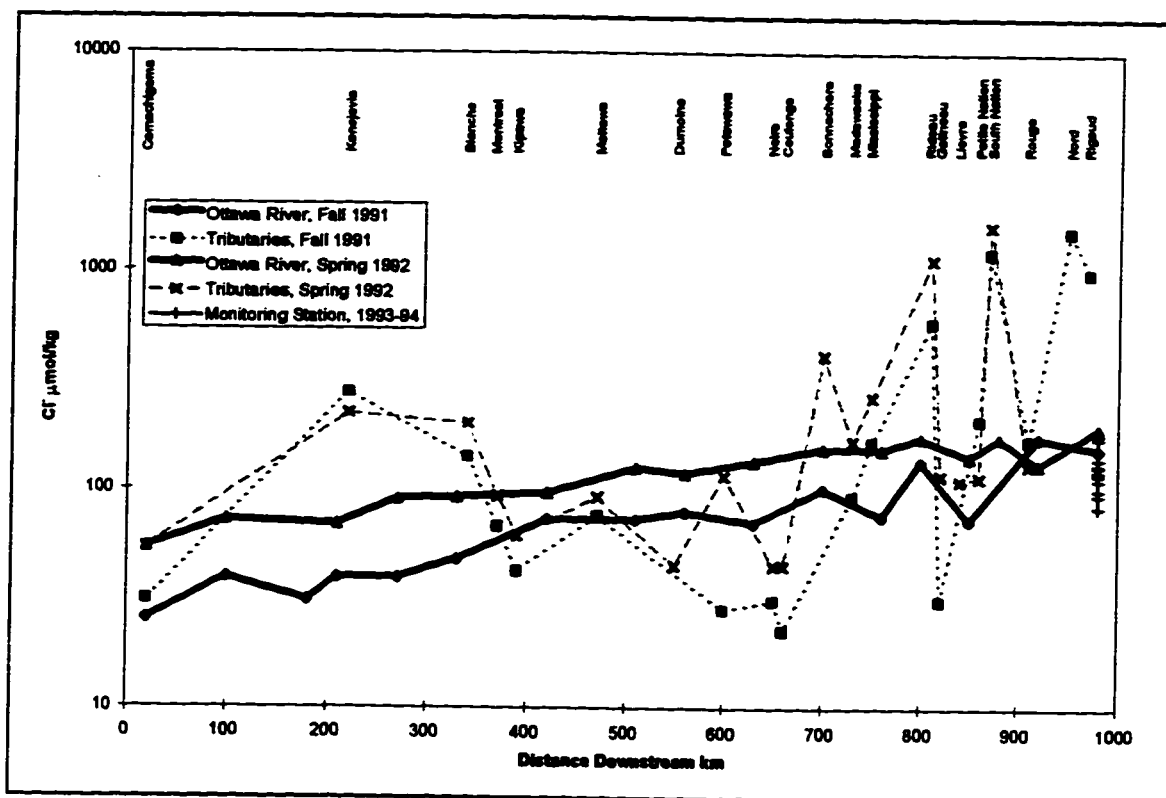


Figure 5-7: Downstream trend of Cl^- concentrations for the spring and fall.

5.2.5 Calculation of Flux

The flux of any element at any position in the Ottawa River basin can be simply calculated by multiplying the volume of water per unit time by the concentration of the element. This is easily done for points along the river where the discharge is measured. Such

points are, however, rare (6 reliable ones) and not always coincident with sampling localities. To alleviate this problem, the relationship between gross drainage area and discharge was explored for different seasons. Figure 5-8 illustrates this relationship and shows that it is very linear and predictable. Gross drainage area for each sample location was calculated via the GIS and inputted into the equation of linear regression for the appropriate season projecting discharge values for all 16 sampling locations along the Ottawa River.

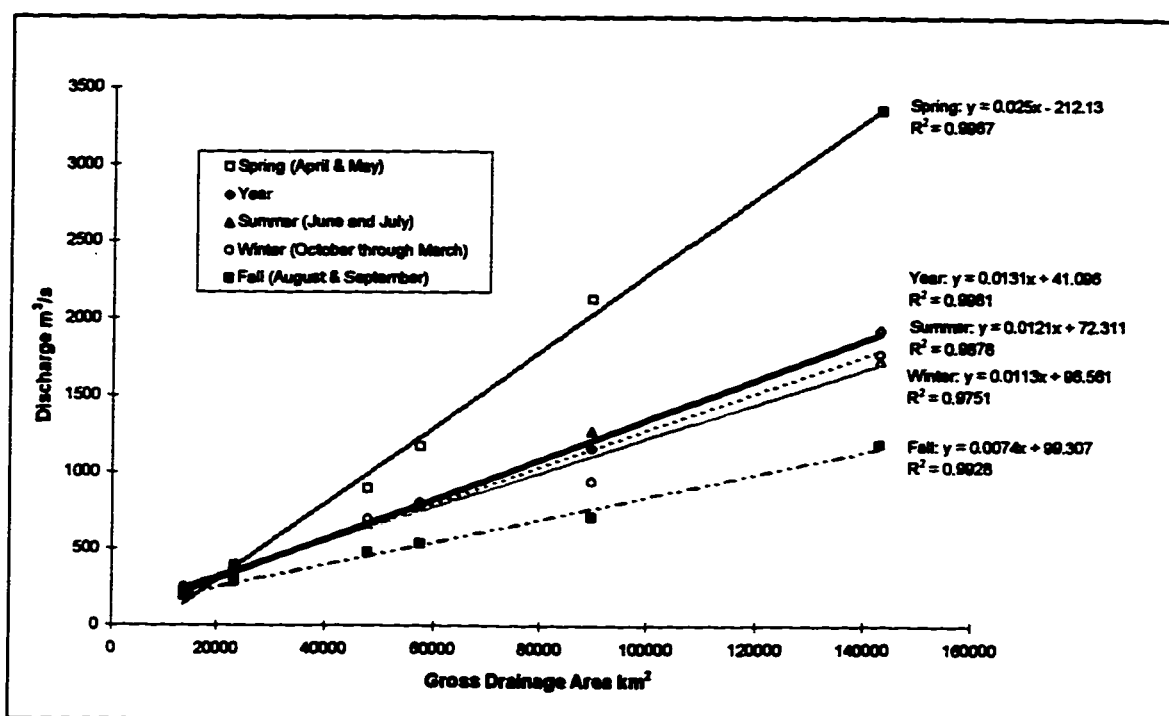


Figure 5-8: Drainage area versus discharge by season for the Ottawa River, data from Atmospheric Environment Service (1994).

Figure 5-9 illustrates the seasonal relationships between discharge and gross drainage area for the major tributaries. These relationships are relatively linear and predictable, but less so than those of the Ottawa River. In this instance, however, the actual discharge data near the mouth of all but three tributaries were available and thus it was mostly not necessary to utilize the above estimates. Quebec tributaries yield more water because they receive more

precipitation and suffer less evapotranspirative loss (see chapter 4 for a more detailed discussion of water balance).

Due to inputs from smaller streams and from ground water, the Ottawa River carries roughly 5% more water annually than that supplied by the tributaries studied here. At shorter time scales this disparity can grow or shrink. For example, in the spring the cumulative water flux of the measured tributaries is equal to that of the Ottawa River, but in the fall it is 28% lower. This is due to factors such as the longer residence time of water in the Ottawa River, flow augmentation practices, and climatic variations. These water balance disparities are resolved at longer time scales but it is reasonable to expect mass imbalances of 10-15% at the seasonal time scale investigated here.

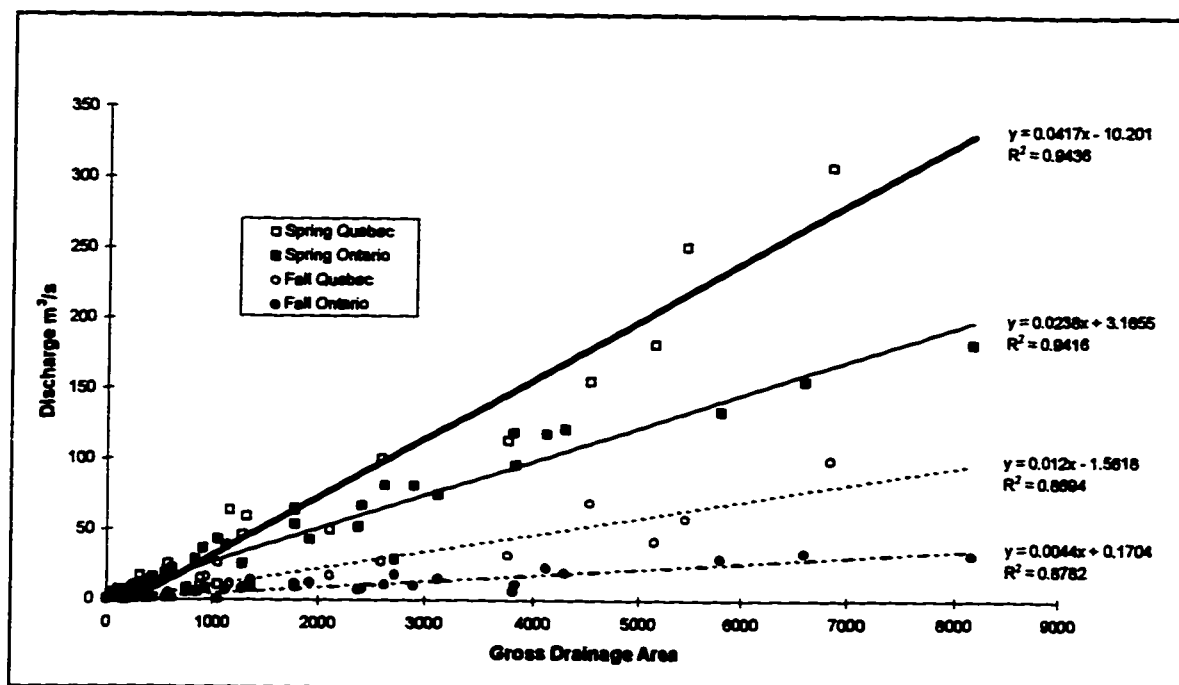


Figure 5-9: Drainage area versus discharge for Quebec and Ontario tributaries during spring and fall; data from Atmospheric Environment Service (1994).

5.2.5a Flux of Cl^-

Figure 5-10 plots fluxes of Cl^- for the Ottawa River and its tributaries for spring and fall as well as the monthly flux at the mouth of the river. The trends for the Ottawa River increase exponentially because both the concentration of Cl^- and the discharge increase downstream. A requisite for conservative ionic behavior is a lack of flux decreases downstream. With the exception of one point in each of the spring and fall in the downstream section of the river, this requisite is met. Poor mixing of incoming dilute tributaries may explain the apparent flux decreases. The flux of Cl^- in the spring, 27% of the annual flux, is almost an order of magnitude higher than the late summer/fall contribution of 3% yet the spring/fall discharge ratio is only 3, indicating that the major source of Cl^- fluctuates seasonally. Road salting seems an obvious candidate for this source but further analysis puts this proposition in question.

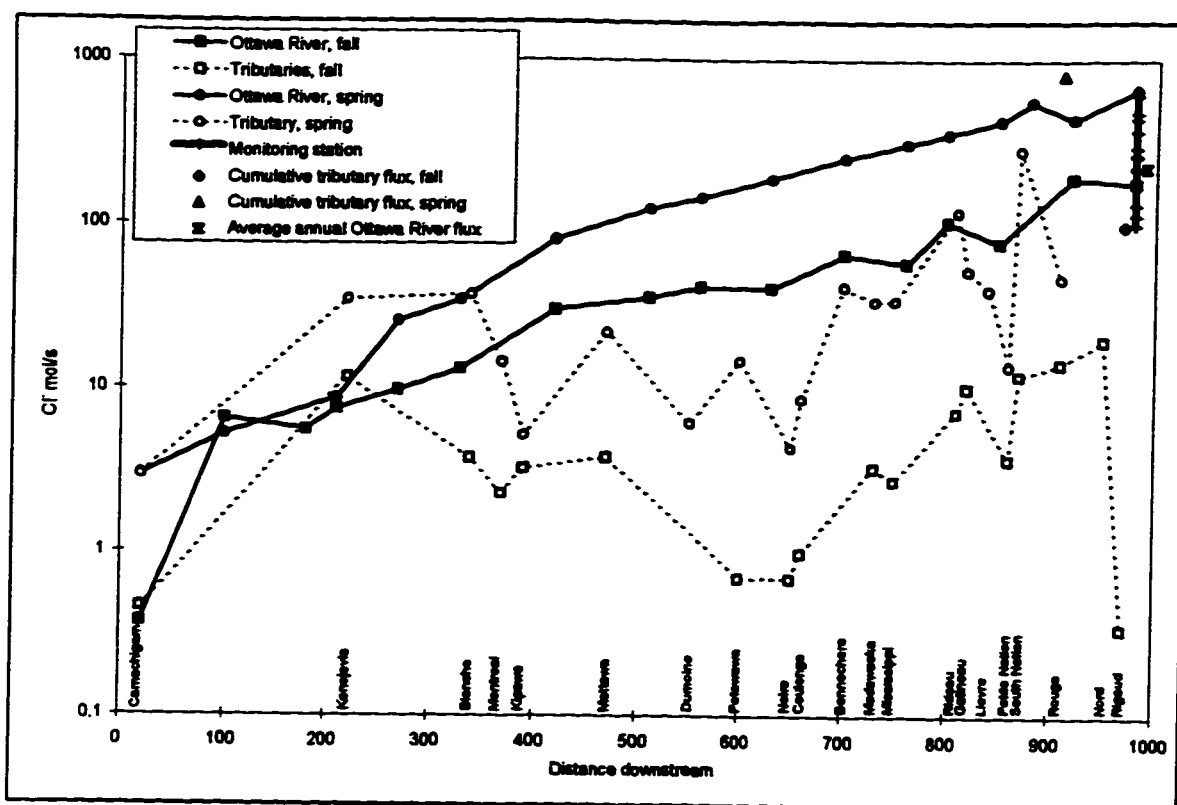


Figure 5-10: Flux of Cl^- from the Ottawa River and its tributaries.

Tributary contributions of Cl^- to the Ottawa River are listed in Table 5-2. The South Nation River is the major source of Cl^- to the Ottawa River. Its importance is superseded in the fall by the Rivière du Nord but this flux is nearly an order of magnitude less than the spring flux. The South Nation River spring/fall discharge ratio is 20, providing a highly seasonally fluctuating source of Cl^- to the Ottawa River. The hydrological reasons for this are discussed in chapter 4. Interestingly, its Cl^- concentration at $1213 \mu\text{mol/l}$ in the fall and $1616 \mu\text{mol/l}$ in the spring is relatively stable and hence its Cl^- flux varies roughly in proportion to its discharge. This suggests that Cl^- originates mainly from long-term baseflow. The South Nation basin is highly developed agriculturally, its rural population is large, its urban population is relatively high, and its basin is largely underlain by Champlain Sea sediments. All of these characteristics are potential sources of Cl^- and it is difficult to quantify their relative importance. Nevertheless, the case for heavy Cl^- loading from road salting is weak.

If a considerable portion of Cl^- from road salting were flushed from the system annually, Howard et al. (1993) claim as much as 45% is, then road salting is an improbable source of Cl^- for the South Nation River, since its Cl^- concentrations vary only by less than 25%. Also, the amount of salt applied to the roads of the South Nation basin is certainly less than that in the greater Ottawa area, yet the Cl^- flux of the South Nation River is by far the largest. This further discounts road salting as a major source of Cl^- . Furthermore, the total flux of Cl^- from the Ottawa River is 267,413 tonnes/year, vastly greater than the total amount of Cl^- applied in the greater Toronto area, some 60,670 tonnes. The amount applied to the Ottawa River basin is unknown but assuredly less than that in Toronto. This is yet another indication that the majority of the Cl^- in the Ottawa River is not of road salt origin. This is especially true if 55% of the annual salt application were retained in the ground water system as proposed by Howard et al. (1993).

Discounting road salt applications as the primary source of Cl^- to the Ottawa River basin, the remaining plausible sources are agricultural fertilizer, leaching of pore waters, shales and marine sediments. Unfortunately, the two sources occupy the same space. During the Pleistocene glaciations, Paleozoic rocks generated and retained till in much greater quantities than the neighbouring Precambrian shield and so soils favorable for agriculture developed primarily over Paleozoic bedrock. These areas occur dominantly in the lowlands which were flooded by the Champlain Sea and were therefore the loci of Quaternary marine sediment accumulation. An estimate of the mass of fertilizer applied and its Cl^- content would allow some constraints to be made but that information has not been gathered for this study. Nevertheless, fertilizer applications, like road salting, are seasonal, and the same arguments apply, discounting fertilizers as a major source of Cl^- to the Ottawa River. In all likelihood,

road salting and fertilizer are important Cl^- contributors, but these fluxes do not exceed the natural ones.

	Spring	Fall
South Nation	34.9%	11.9%
Rideau	14.6%	7.1%
Gatineau	6.4%	10.0%
Rouge	5.8%	14.2%
Bonnechere	5.1%	
Rivière du Lièvre	4.9%	
Blanche	4.5%	3.7%
Kenojevis	4.2%	11.4%
Mississippi	4.2%	2.7%
Medawaska	4.2%	3.3%
Mattawa	2.6%	3.7%
Petawawa	1.8%	0.7%
Montreal	1.8%	2.2%
Petite Nation	1.7%	3.7%
Coulonge	1.0%	1.0%
Dumoine	0.7%	
Kipawa	0.6%	3.2%
Noire	0.5%	0.7%
Camachigama	0.4%	0.4%
Nord		19.7%
Rigaud		0.3%

Table 5-2: Tributary contribution of Cl^- to the Ottawa River for the spring and fall, in order of decreasing spring contribution.

5.3 CARBON

The carbon cycle is the dominant control on acid-base reactions in the Ottawa River basin, as it is for most natural surface waters (Drever, 1988). It thus plays an important role in the behavior of most dissolved chemical species, Cl^- and Na^+ being the main exceptions. It is therefore useful to discuss the carbon cycle before discussing the behavior of other dissolved species.

Dissolved inorganic carbon (DIC) enters waters in the Ottawa River basin from primarily three sources: the atmosphere, soil and ground water respiration, and from dissolution of carbonate rocks. The first two sources involve equilibration of CO_2 with water

which can be summarized by the following three equations (Drever, 1988; Stumm and Morgan, 1996):



These reactions are dependent on the activity of the hydrogen cation (pH). As a result, if the pH and partial pressure of CO_2 are known, the activity (activity and concentration are essentially equivalent for dilute waters) of each carbonate species can be calculated from Henry's Law, the law of mass action, and the expression for the equilibrium constant as follows:

$$a_{H_2CO_3} = K_{CO_2} \cdot pCO_2 \quad \dagger \quad \text{Equation 5-6}$$

$$a_{HCO_3^-} = \frac{K_1 \cdot K_{CO_2} \cdot pCO_2}{a_{H^+}} \quad \text{Equation 5-7}$$

$$a_{CO_3^{2-}} = \frac{K_2 \cdot K_1 \cdot K_{CO_2} \cdot pCO_2}{a_{H^+}^2} \quad \text{Equation 5-8}$$

The sum of the activities of the three species is the total dissolved inorganic carbon (henceforth DIC) (Skirrow, 1975; Drever, 1988). The values for the equilibrium constants are temperature dependent and are determined empirically by experiment. Regression of published data (Drever, 1988) for the temperature range $T = 0-30^\circ C$ yields the following algebraic expressions for K:

[†] For convenience, it has been common practice in the literature to lump together the hydration of $CO_2(g)$ into $CO_2(aq)$ and the protolysis of $CO_2(aq)$ into $H_2CO_3(aq)$, using the composite equilibrium constant K_{CO_2} , and to express the sum of the activities of $CO_2(aq)$ and $H_2CO_3(aq)$ simply as the activity of $H_2CO_3(aq)$. The true activity of $H_2CO_3(aq)$ is lower and can be determined from the relationship $K_{CO_2} = K_{H_2CO_3}/(1+K)$, where K is the constant describing the hydration equilibrium (Stumm and Morgan, 1996). For the purposes of this study, the use of the composite equilibrium constant K_{CO_2} is sufficient and henceforth the activity of $H_2CO_3(aq)$ includes the activity of $CO_2(aq)$.

$$K_{CO_2} = -2.22 \times 10^{-6} T^3 - 1.91 \times 10^{-5} T^2 + 1.63 \times 10^{-2} T + 1.11 \quad \text{Equation 5-9}$$

$$K_1 = 1.67 \times 10^{-4} T^2 - 1.34 \times 10^{-2} T + 6.58 \quad \text{Equation 5-10}$$

$$K_2 = -2.22 \times 10^{-6} T^3 + 2.29 \times 10^{-4} T^2 - 1.62 \times 10^{-2} T + 10.6 \quad \text{Equation 5-11}$$

The r^2 value for all three equations is higher than 0.99.

5.3.1 Rain water

Using a pCO_2 of 350ppm for the modern atmosphere (Schlesinger, 1991), a pH of 5 (Schindler et al., 1976; Barrie and Hales, 1984) and a temperature of 3.5°C for average rain water in the Ottawa River basin and ignoring the small influences of other ions, the activity of the carbonate species in rain water is calculated to be: $H_2CO_3 = 10^{-4.75}$; $HCO_3^- = 10^{-6.21}$; $CO_3^{2-} = 10^{-11.7}$; and therefore the average DIC of precipitation in the Ottawa River basin is $\sim 10^{-4.73}$ or 1.84×10^{-5} mol/l. In fact, this estimate is probably slightly high for two reasons: (1) snow contains negligible DIC and roughly 25% of the precipitation that falls in the basin is snow; and (2) the dissolution of CO_2 is inversely proportional to temperature and if the winter months are removed from the average annual temperature calculation, because no DIC is contributed during that time, the calculated average basinal temperature increases and the dissolution of CO_2 decreases. Taking these factors into account, the estimate becomes 1.3×10^{-5} mol/l. However, it is possible that during spring snow melt, the very cold meltwaters ingass CO_2 making the above refinement unnecessary. Both calculated values fall into the typical range of 10^{-5} to 5×10^{-5} for DIC in rain water (Stumm and Morgan, 1996).

The $\delta^{13}C$ for DIC in rain water is a function of atmospheric $\delta^{13}C$, which ranges from -6 to -8‰ PDB (Cerling et al., 1991) and has an average of -7‰ PDB (Faure, 1986), and the fractionation of carbon isotopes between atmospheric CO_2 and aqueous carbonate species,

which ranges from $9.2 \pm 0.4\text{‰}$ at 0°C to $6.8 \pm 0.4\text{‰}$ at 30°C (Deuser and Degens, 1967).

Using an average temperature of 7°C and the average atmospheric $\delta^{13}\text{C}$ value of -7‰ , waters in equilibrium with the atmosphere in the Ottawa basin, including the average rain water, should have $\delta^{13}\text{C}$ of about $+1.4\text{‰}$ PDB.

5.3.2 Soil water

Due to root respiration, oxidation of organic material and bacterial respiration, the soil atmosphere is considerably richer in CO_2 than the atmosphere. Reardon et al. (1979) have observed consistent values of 0.4% CO_2 at depths greater than 6m in sandy calcareous soils in southern Ontario, soils similar to those of the lowlands in the Ottawa River basin. At depths less than 6m, seasonal variations were observable, with the maximum at 2m having 0.1% CO_2 in the winter and $>1\%$ in the summer. $p\text{CO}_2$ values as high as $10^{-0.5}$ atm ($\sim 30\%$) have been observed in soils (Stumm and Morgan, 1996). Utilizing equation 5-6, soil waters in equilibrium with 1% CO_2 would have a DIC of $340\mu\text{mol/l}$.

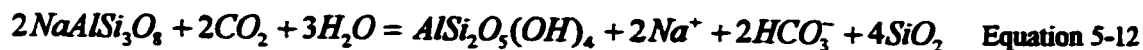
The $\delta^{13}\text{C}$ of soil CO_2 is derived primarily from $\delta^{13}\text{C}$ of organic material which typically has a value of -24 to -34‰ , with an average of -28‰ (Faure, 1986). No fractionation occurs when this material is respired to produce CO_2 gas. The difference in the diffusion coefficients of $^{12}\text{CO}_2$ and $^{13}\text{CO}_2$ cause soil gases to be enriched in $^{13}\text{CO}_2$ by up to 4.4‰ (Cerling et al., 1991), relative to the organic source material. As a consequence, the average soil gas has $\delta^{13}\text{C}$ of -30 to -20‰ , with an average of $\sim -24\text{‰}$. The dissolution of this gas in soil water is subject to the same fractionation as the above discussed dissolution of atmospheric CO_2 into rain water so that average soil waters have $\delta^{13}\text{C}$ of -23 to -13‰ , with an average of -17‰ .

Some constraints can be placed on these values in the Ottawa River basin. The $\delta^{13}\text{C}$ values of particulate carbon in the St. Lawrence River in the spring, when the Ottawa River supplies as much as 50% of the discharge (CSL (Centre Saint-Laurent), 1992), are -27‰ (Tan, 1987). This value is therefore assumed to be the average for organic carbon in the Ottawa River basin. Applying a fractionation factor of +4‰ for diffusion and +7‰ for dissolution of $\text{CO}_2(\text{g})$ yields a $\delta^{13}\text{C}$ of -16‰ PDB for waters in equilibrium with the average soil gas in the Ottawa River basin.

5.3.3 River water

Figure 5-11 shows the downstream trend of DIC values in the Ottawa River basin. The distribution of DIC in the Ottawa River basin is strongly controlled by geology. On average, the DIC of the tributaries ranges from about 45 $\mu\text{mol/l}$ for those draining purely silicate terrain in the headwaters to about 3000 $\mu\text{mol/l}$ for those draining carbonate catchments. The values for the Ottawa River reflect the mixing of its tributaries, falling between 55 $\mu\text{mol/l}$ in the headwaters to 700 $\mu\text{mol/l}$ at the mouth. The Pearson correlation coefficient of DIC and the abundance of carbonate rocks in tributary basins is 0.89.

The dilute waters in the uplands, with an average DIC of 55 $\mu\text{mol/l}$, are only 4 times more concentrated than rain water and, after evapotranspiration is accounted for, $\sim 45\%$ of the DIC can be explained by precipitation input (Table 5-1). Note, however, that this calculation is less meaningful than that for Cl^- , because DIC is much less conservative. These low values can be explained by two reasons: (1) soils are thin and discontinuous in the Canadian Shield (Kaszycki and Shilts, 1987; Kaszycki, 1987) limiting the production of soil CO_2 . Furthermore, lower growth rates in the northern parts of the basin would also yield less CO_2 from root respiration. (2) Low weathering rates. Weathering of minerals consumes CO_2 by transforming it into HCO_3^- . By reducing the pCO_2 of water, weathering increases the difference between the partial pressure of CO_2 in the gas and the liquid phase, thus increasing the rate of CO_2 diffusion into the liquid. For example:



Both reactions, the weathering of albite (equation 5-12) and limestone (equation 5-13), consume CO_2 . High weathering rates thus produce waters with high DIC concentrations.

Weathering rates in the Canadian Shield are relatively low (Frape and Fritz, 1987) due to the resistant nature of the bedrock and the lack of soils and fine grained materials, without which rock-water interaction is limited. In the headwaters, low weathering rates limit the fixing of carbon as bicarbonate, and waters draining these areas therefore contain little DIC.

Further down-stream, as more weatherable materials such as Grenville marbles and Paleozoic carbonates, and more weatherable environments, soils and tills, become plentiful, DIC increases. The highest DIC was recorded in the South Nation River which drains a basin with abundant carbonates, tills, clays and soils, has the warmest climate of all tributary basins, and is heavily used for agriculture which enhances weathering by increasing water-rock interaction by churning soils.

5.3.4 Temporal distribution

As discussed in chapter 4, the natural discharge cycle in the uppermost portions of the river (0-300km) is drastically altered by hydro-electric operations, with discharges essentially the inverse of their natural rhythm. Seasonal chemical variations in this stretch of the river are thus more difficult to interpret. The tributaries, however, are relatively unaltered on a seasonal basis (Rivière Gatineau and Lievre excepted) and, as a result, natural seasonal chemical fluctuations are best observed in the tributaries and in the lower stretches of the Ottawa River.

Figure 5-11 shows that DIC concentrations in the fall and the spring are roughly comparable, with the higher concentration from either season, depending on the tributary or the stretch of the river. However, as Figure 5-12 illustrates, the concentration of DIC can fluctuate strongly over the year. DIC concentrations peak in the spring and the late fall (roughly 6 weeks after the fall sampling campaign) along with discharge. This temporal trend is evident for most of the major ions. This behavior is contrary to the dilution trends commonly reported in the literature (Johnson et al., 1969; Hem et al., 1990; Riggs and Harvey, 1990; Schlesinger, 1991) where increasing discharge is accompanied by decreased concentrations, due to dilution of baseflow, or to dilution of “old” water by “new” water with lower solute concentrations. Indeed, recent experimental results strongly challenge the concept of dilution. For example, Anderson et al. (1993), in catchment scale sprinkler experiments, have observed concentration decreases with increasing discharge even when the applied rainfall had higher solute concentrations than the baseflow (the opposite of dilution models). This suggests that all storm and flood runoff undergoes significant chemical reaction with soil or bedrock.

The reverse dilution trend in the Ottawa River is likely caused by two processes. (1) Seasonal fluctuations in the contribution of concentrated tributary waters. Lowland tributaries have much higher flow variability than their upland counterparts, with the highest contribution to ion budget of the Ottawa River in the spring and fall when they are most active (chapter 4). Since they often contain total dissolved solids at concentrations an order of magnitude greater than the upland tributaries, the total dissolved solids of the Ottawa River increases along with its increasing discharge. (2) Hysteresis. It is a process whereby highly concentrated waters

that have accumulated in the soil and ground water system during periods of low flow are flushed out during storms or seasonal flooding (Schlesinger, 1991). Some conditions in the Ottawa River basin are conducive to hysteresis. As discussed in chapter 4, all summer precipitation is evapotranspired producing a strong summer/early-fall drawdown which ends with the cessation of transpiration by frost. During the drawdown, residual waters in the soil and ground water system have more time to interact with minerals and soil gases than is the case during high flow periods, thus producing the accumulations of concentrated waters thought to cause hysteresis. Winter drawdown should behave in the same manner, except that chemical weathering rates would be lower due to the lower temperature and lower CO₂ production in soils. Higher tributary concentrations in the spring than in the early fall (at flow minima), such as exist for most of the lowland tributaries, are suggestive of hysteresis.

Some upland tributaries do follow the classical dilution trend with lower concentrations in the spring than the fall. For these tributaries, low rates of weathering and sparse soils probably prevent waters from becoming concentrated during periods of low flow, suggesting that geology controls the level of hysteresis. However, for the temporal behavior of DIC and other major ions in the Ottawa River, seasonal fluctuations in the contribution of concentrated tributary waters are certainly the most important factor. Hysteresis and dilution trends are secondary.

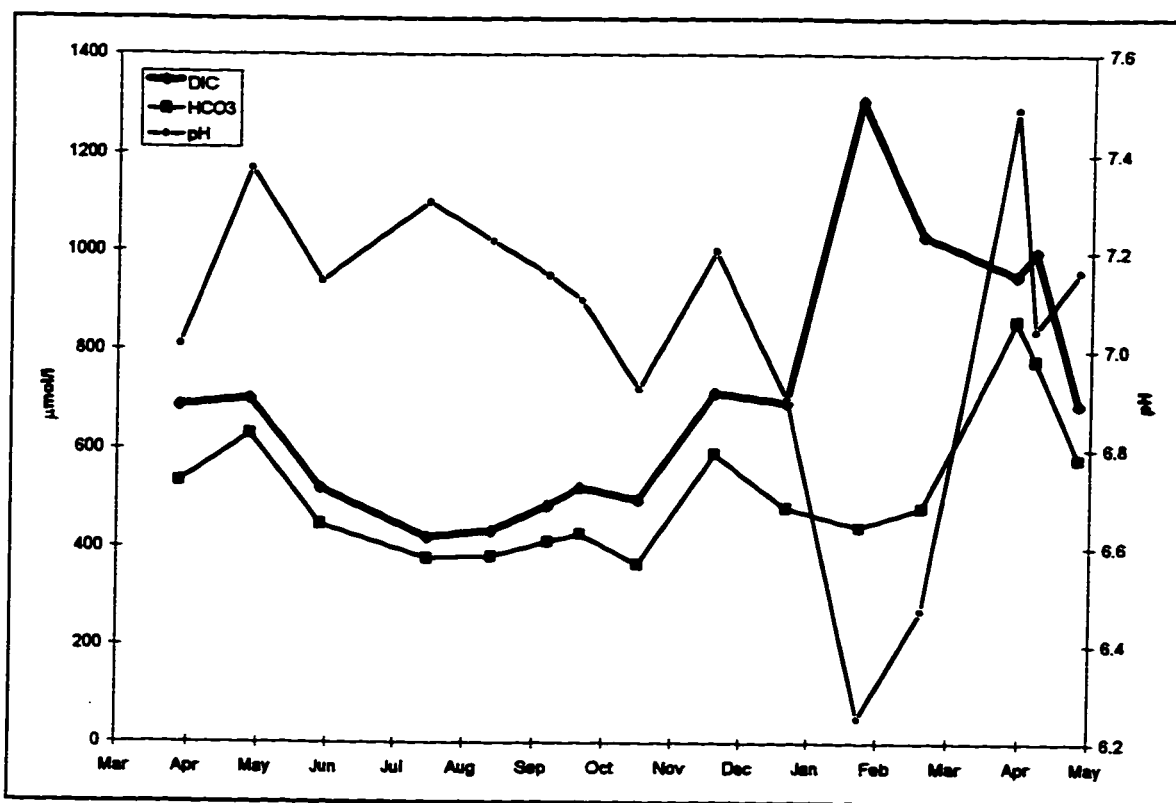


Figure 5-12: Monthly DIC, HCO_3^- , and pH at the mouth of the Ottawa River.

Figure 5-12 also shows the monthly fluctuations of pH and HCO_3^- (bicarbonate) at the mouth of the Ottawa River, illustrating the pH dependent relationship between DIC and HCO_3^- . At pH less than 7, H_2CO_3 becomes an important contributor to DIC and HCO_3^- is no longer an effective proxy for the carbon budget. At pH 6.4, HCO_3^- and H_2CO_3 are in equal concentrations (for a proof of these relationships see Drever, 1988). This was the case in February and March of 1994 when roughly half of the DIC in the Ottawa River was H_2CO_3 and the DIC was at its maximum at a time when HCO_3^- was at intermediate values. These relationships are stressed here because frequently, in the literature (Pawellek and Veizer, 1994; Cameron et al., 1995; Flintrop et al., 1995; Yang et al., 1996), plots of ionic species or isotopic compositions versus HCO_3^- are used to characterize weathering or biological

processes. However below ~pH 7, correlations with HCO_3^- become less meaningful and DIC should be used instead.

5.3.5 Isotopic Constraints

5.3.5a Spatial Isotope Distribution

The $\delta^{13}\text{C}_{\text{DIC}}$ along the length of the Ottawa River ranged from -17.4‰ in the headwaters to -8.4‰ in the lowlands in the fall and from -17.3 to -7.3‰ in the spring. In general, the spring values are lighter (Figure 5-13). The $\delta^{13}\text{C}_{\text{DIC}}$ values for the tributaries fall within the same range with the exception of some lowland tributaries which have slightly heavier values of up to 6.6‰. The values for the Ottawa River and its tributaries are comparable to, or slightly lighter than, those for the Rhine (-10.5 to -7.1‰) and its tributaries (-14.4 to -6.7‰) (Buhl et al., 1991; Flintrop et al., 1995). The values of the carbonate bedrock dominated lowland tributaries and of the lower reaches of the river are also comparable, but slightly lighter than, for the carbonate bedrock dominated Danube and Fraser Rivers (~-7.5‰) (Pawellek and Veizer, 1994; Cameron et al., 1995). These ^{13}C -depleted values show that respiration plays an important role in the isotopic composition of waters in the Ottawa River basin. In fact, it can be shown that respiration provides half or more of the DIC in all these waters.

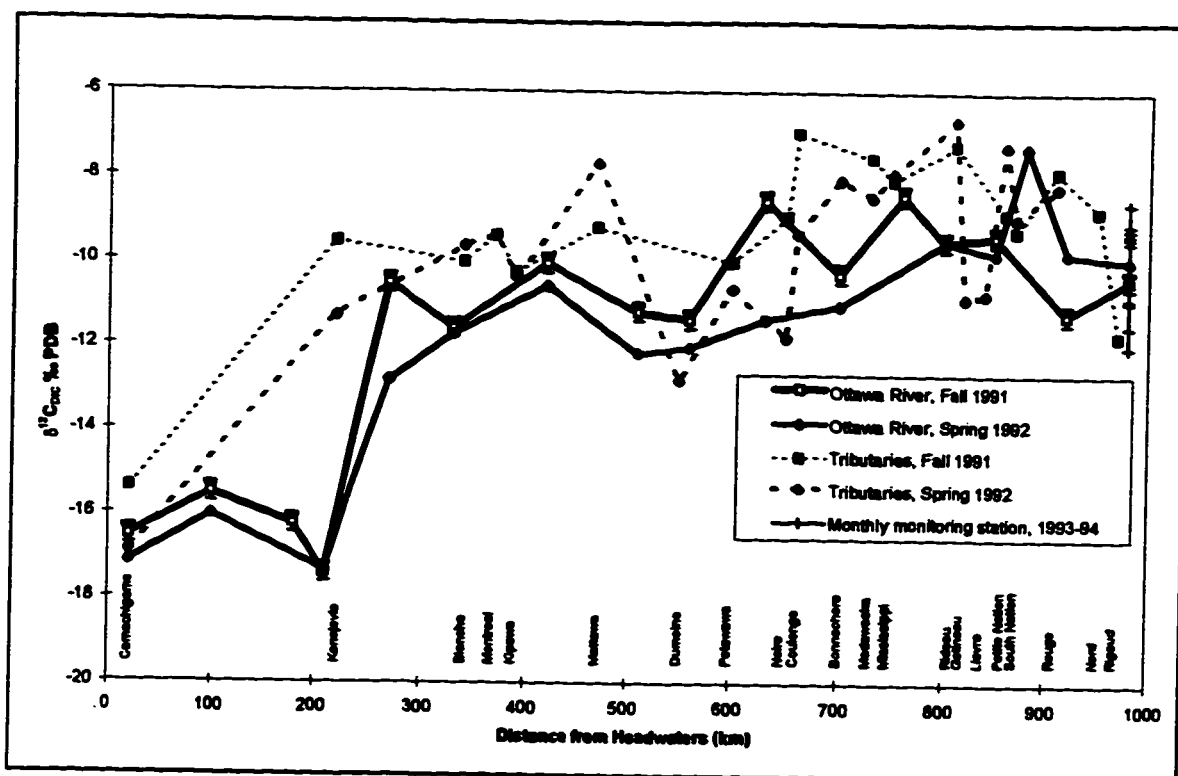


Figure 5-13: Carbon isotopic composition of dissolved inorganic carbon ($\delta^{13}\text{C}_{\text{DIC}}$) in the Ottawa River basin. Analytical error bars are shown on the river trend for the fall.

5.3.5b Sources of Carbon

The sources of carbon in river water are primarily from: 1) CO_2 enriched soil waters, 2) the dissolution of carbonates, 3) direct inputs from precipitation, 4) exchange with atmospheric CO_2 , and 5) photosynthesis/respiration within the river. Direct inputs from precipitation are certainly minuscule and accepting, for the moment, that the latter two sources are inconsequential or secondary, we are left with two endmembers, carbon from respiration and from carbonate weathering. As discussed in the section on soil water (5.3.2), the respiration endmember has a $\delta^{13}\text{C}_{\text{DIC}}$ of $\sim -16\text{‰}$. Carbonates in the Ottawa Embayment of the St. Lawrence Lowlands have $\delta^{13}\text{C}$ of -5.3 to $+1.9\text{‰}$, with an average of -0.5‰ (Taylor and Sibley, 1986; Brand and Terasmae, 1984; Middleton et al., 1990; Fortin and Tasse, 1987). The dissolution of carbonate by carbonic acid:



, where C_{carb} is carbon from carbonate with a $\delta^{13}C$ of -0.5‰ and C_{resp} is carbon from the respiration of organic material with a $\delta^{13}C$ of -16‰, yields a $\delta^{13}C$ of -8.25‰ for the carbonate weathering endmember (C_{cw}). The carbon isotope composition of all waters in the Ottawa basin can be explained by these two endmembers (Figure 5-14). Minor deviations can result from either the variability in the endmember composition (e.g. carbonate rocks with $\delta^{13}C$ of -5‰ or organic material with $\delta^{13}C$ of -14‰ from C4 plants) or from fluxes of carbon from other sources, such as an exchange with the atmosphere or photosynthesis- respiration in the river. These fluxes are almost certainly of secondary importance since the observed isotopic discrepancies from the model are within ± 1.65 ‰. Such discrepancies will be discussed further below.

5.3.5c Weathering

Figure 5-14 plots DIC versus $\delta^{13}C_{DIC}$ for all samples and suggests mechanisms for the formation of different fields on the plot. Since silicate weathering does not yield any additional carbon from a solid phase (equation 5-12) it fixes only soil CO_2 . It also proceeds at a much slower rate than carbonate weathering, and therefore produces waters with low DIC and “respiration” $\delta^{13}C_{DIC}$ values of ~ -16 ‰. These waters plot to the lower left of Figure 5-14. In a limited system (fixed amount of CO_2 or carbonate material), such as might occur in sparse soils or the wintertime when soil CO_2 production is much lower, the weathering of carbonate would proceed until the supply of CO_2 is exhausted, producing waters with moderately increased DIC and $\delta^{13}C_{DIC}$ of ~ -8 to -10 ‰ in accordance with dominantly carbonate weathering. Such waters are circled in the upper left of Figure 5-14. A similar water could be

produced by catchments with only limited amounts of carbonate. Runoff from the remaining areas of silicate bedrock would dilute the DIC concentration but because silicate waters are so low in DIC, the $\delta^{13}\text{C}$ signal would carry a dominantly carbonate weathering signal. It is likely that both scenarios are responsible for the waters in question, since limited CO_2 supplies occur in the areas underlain by silicate geology in the Ottawa River basin.

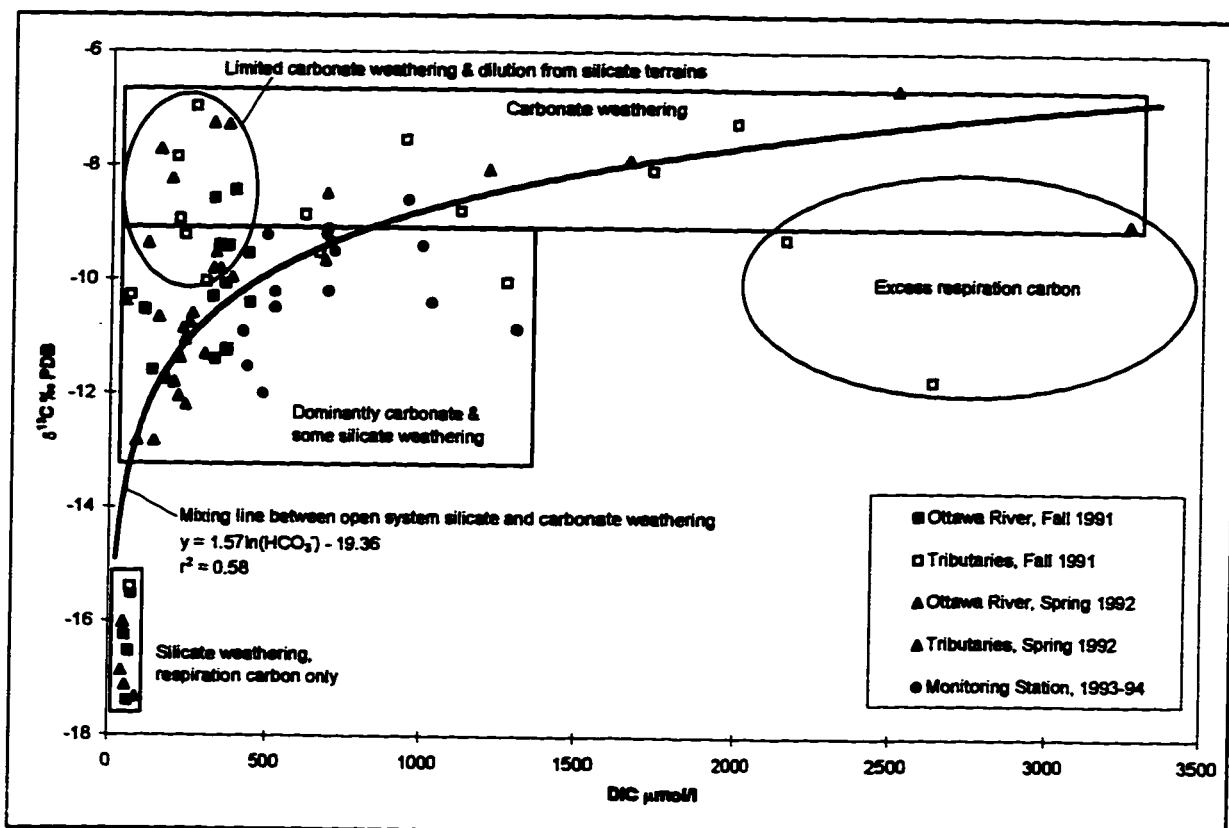


Figure 5-14: DIC versus $\delta^{13}\text{C}_{\text{DIC}}$ for the Ottawa River and its tributaries

Waters in contact with a generous supply of both CO_2 and carbonate plot in the upper centre and upper right portion of Figure 5-14. These waters dissolve carbonate until calcite saturation is reached at which time, if CO_2 is sufficiently abundant, they begin to acquire a stronger respiration $\delta^{13}\text{C}_{\text{DIC}}$ signal. Figure 5-15, which plots calcite saturation versus $\delta^{13}\text{C}_{\text{DIC}}$, illustrates this trend clearly.

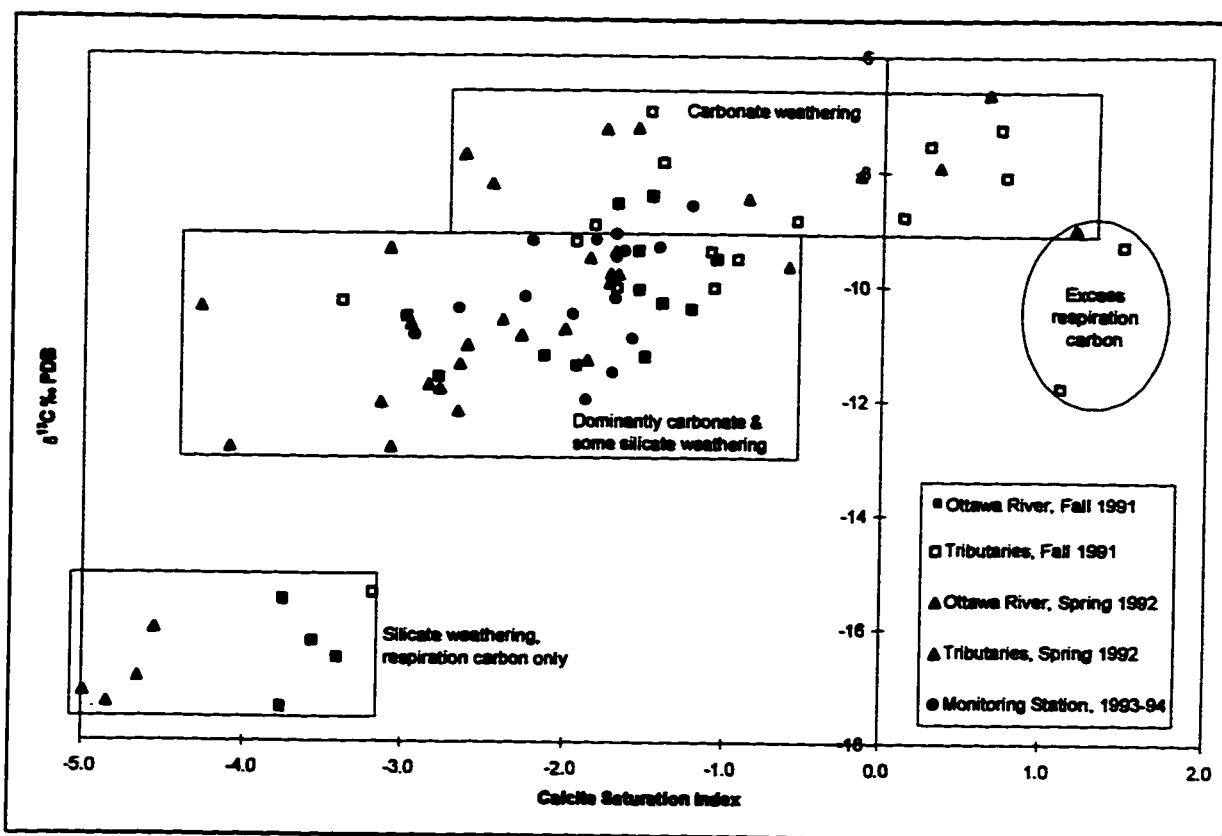


Figure 5-15: Calcite saturation index versus $\delta^{13}\text{C}_{\text{DIC}}$ for the waters of the Ottawa River basin.

5.3.5d Temporal Trends

Seasonal $\delta^{13}\text{C}_{\text{DIC}}$ trends are indistinct if compared to the spatial ones, with the average difference between spring and fall samples for the same locality being less than 1‰. Figure 5-16 shows the fluctuations of $\delta^{13}\text{C}_{\text{DIC}}$ at the mouth of the Ottawa River for the year 1993/94. The most ^{13}C depleted values occur in the summer, the opposite of what would occur if photosynthesis were influencing the signal. In the summer, a greater percentage of discharge is provided by the upland tributary basins which have a more depleted signal. During spring and late fall when the hydrograph rises, greater percentages of water come from the lowland tributaries which have relatively ^{13}C enriched values. This suggests that $\delta^{13}\text{C}_{\text{DIC}}$ of the sources of DIC in the basin are relatively fixed and operate on time scales longer than 6 months (seasonally).

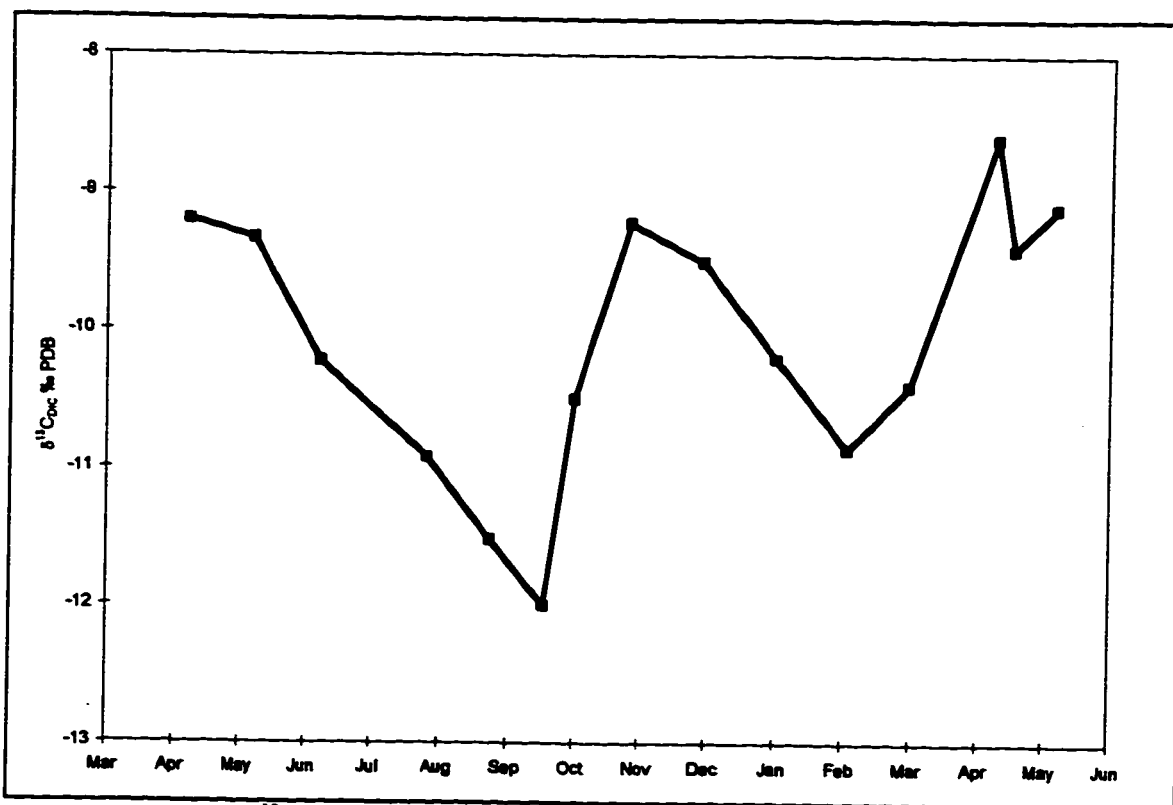


Figure 5-16: Monthly $\delta^{13}\text{C}_{\text{DIC}}$ at the mouth of the Ottawa River.

5.3.6 pCO_2

5.3.6a Spatial Distribution

The partial pressure of carbon dioxide (pCO_2) in the Ottawa River and its tributaries is a function of CO_2 inputs from respiration, which increase the pCO_2 and lower the pH, and mineral weathering, which consumes H^+ and converts carbonic acid into bicarbonate, increasing pH and lowering pCO_2 (equation 5-12 and 5-13). The relative effectiveness of these processes varies spatially in the basin with the abundance of carbonates and soils. Upland silicate basins are characterized by low soil CO_2 respiration due to their sparse soils but because they are resistant to chemical weathering, the neutralization of carbonic acid is limited and pCO_2 values remain at or higher than atmospheric levels. Lowland carbonate basins have thick productive soils but because carbonate weathering rates are high, the

neutralization of carbonic acid is rapid yielding $p\text{CO}_2$ values not much higher than those of the upland silicate basins. Figure 5-17 illustrates the downstream trend of $p\text{CO}_2$.

5.3.6b Temporal Distribution

Seasonally, $p\text{CO}_2$ is higher in the spring than the fall. Three reasons can account or contribute to this. (1) Hysteresis, where waters rich in soil CO_2 are flushed from the system during seasonal flooding. (2) Rain and snow have low pH (~ 5) and thus spring flooding releases a wintertime of stored acid into the drainage network driving the $p\text{CO}_2$ up. This can be augmented by anthropogenic contributions to the acidity of precipitation or what is commonly referred to as "acid rain" which can be considerable in the Ottawa River basin (Environment Canada, Inland Waters and Lands Directorate, 1988; Environment Canada, Lands Directorate, Environmental Conservation Service, 1985). (3) Photosynthesis in the summer and fall consumes more CO_2 than respiration contributes lowering the $p\text{CO}_2$ of fall waters.

The fluctuations in pH and $p\text{CO}_2$ at the mouth of the Ottawa River (Figure 5-18) are of too large a magnitude and occur too early in the spring to be explained by respiration or photosynthesis alone, suggesting that hysteresis and spring acid release are the main controls on the seasonal fluctuations in $p\text{CO}_2$. The $\delta^{13}\text{C}_{\text{DIC}}$ values at the mouth of the river (Figure 5-16), as discussed above, also belie photosynthetic CO_2 drawdown in the fall. Further evidence suggesting that photosynthesis-respiration do not play a major role in the $p\text{CO}_2$ budget is the fact that oxygen is undersaturated in the fall and oversaturated in the spring (Figure 5-19), the opposite of what should occur if the rate of photosynthesis exceeded that of respiration in the fall. The fact that $\delta^{13}\text{C}_{\text{DIC}}$ values are slightly enriched in ^{13}C in the fall at most localities (Figure

5-13), as would be expected for in-river photosynthesis, does suggest that photosynthesis/respiration could influence the carbon budget in a secondary nature. However, Aravena et al. (1992) and Schiff et al. (1990), have documented that soil $\delta^{13}\text{C}_{\text{DIC}}$ values in the silicate Harp Lake watershed (50km outside the Ottawa River basin) have a seasonal cycle where they are lightest in the winter (-25‰) and heaviest in the summer/fall (-23‰). They attribute this to lower losses by diffusion to the atmosphere during winter because of the snow cover, which allows a slight accumulation of CO_2 in the soil zone. This seasonal 2‰ difference in the source of $\delta^{13}\text{C}_{\text{DIC}}$ can fully account for the seasonal differences observed in the waters of the Ottawa River basin ($\pm 2\text{‰}$) suggesting that fluctuations in soil and ground water conditions are a stronger secondary control on the $\delta^{13}\text{C}_{\text{DIC}}$ of waters in the Ottawa River basin than in-river photosynthesis-respiration.

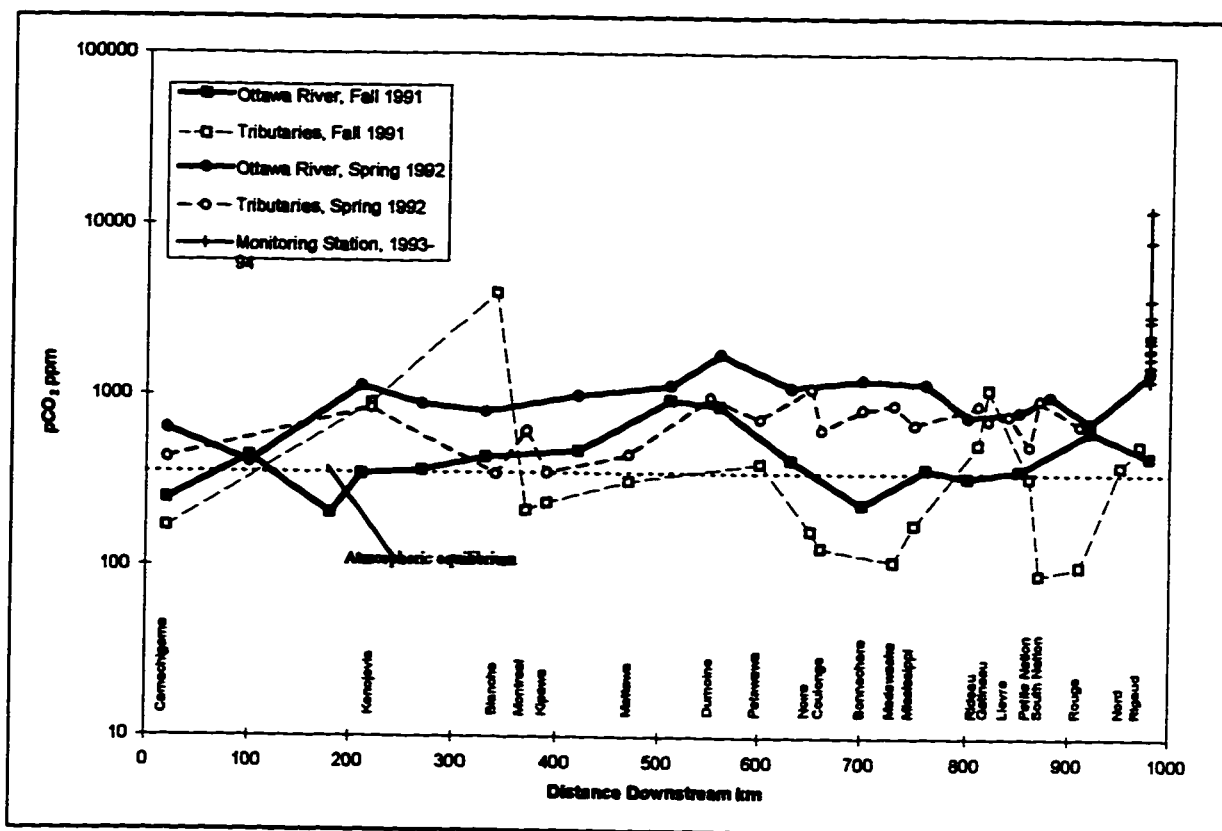


Figure 5-17: pCO_2 versus distance downstream for the Ottawa River and its tributaries.

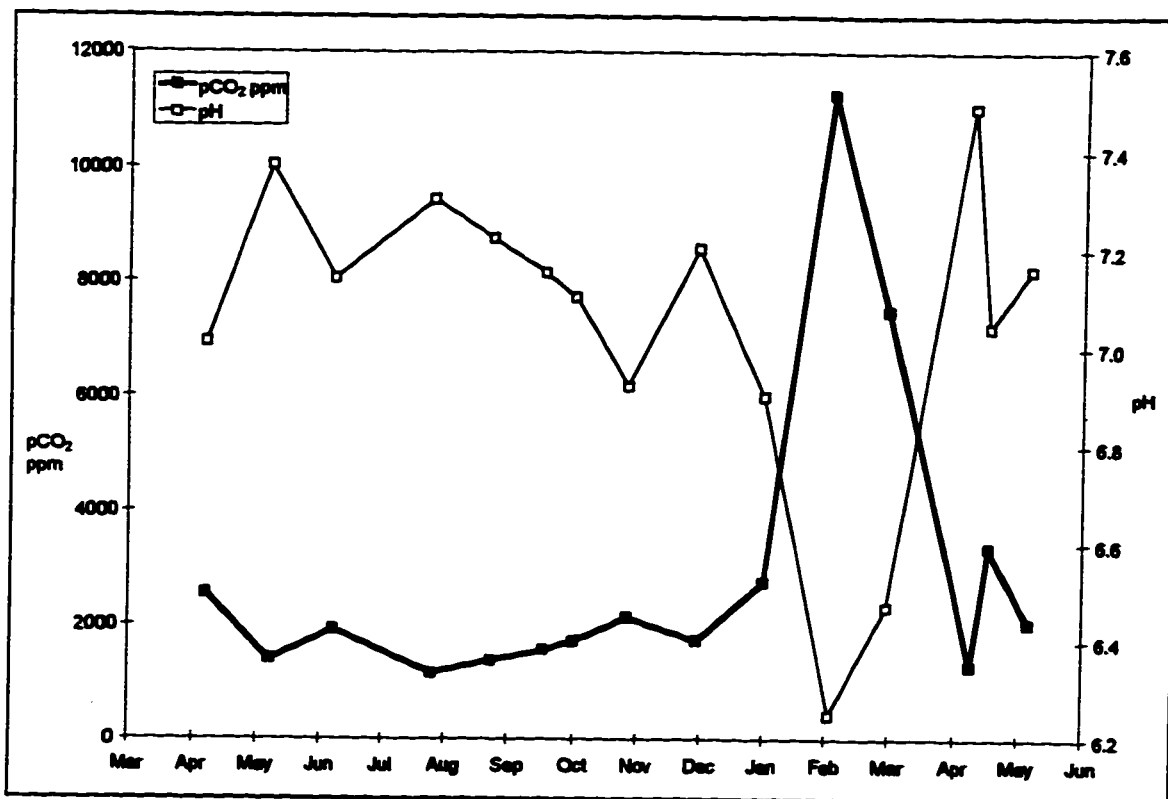


Figure 5-18: Monthly pCO₂ and pH at the mouth of the Ottawa River, 1993/94.

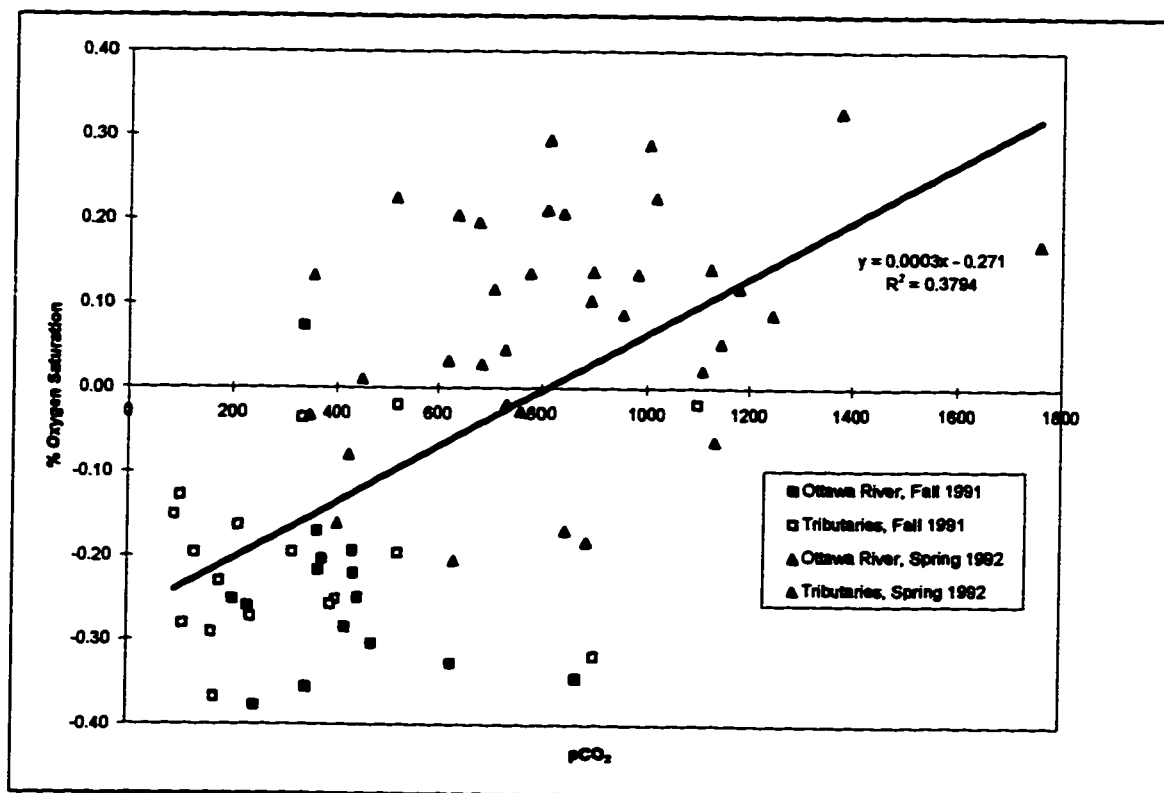


Figure 5-19: Oxygen saturation versus pCO₂ for the Ottawa River and its tributaries, fall and spring.

5.3.6c Origin

Figure 5-20 plots carbon isotopes against $p\text{CO}_2$. Pathways and processes for the conversion of soil water into observed river waters are shown. The $p\text{CO}_2$ value for the hypothetical soil water was chosen for the convenience of display, it is not accurate since undoubtedly much higher $p\text{CO}_2$ may exist in some soils in the basin. The average $\delta^{13}\text{C}_{\text{DIC}}$ for soil waters was calculated above in section 5.3.2. Silicate weathering consumes CO_2 but contributes no additional carbon to waters (equation 5-12). As a result, $p\text{CO}_2$ values are reduced but the $\delta^{13}\text{C}_{\text{DIC}}$ of resulting waters retains a respiration signal. These waters plot in the lower left of Figure 5-20. Carbonate weathering (equation 5-13) proceeds at much higher rates than silicate weathering and contributes $\delta^{13}\text{C}_{\text{carbonate}}$ of $\sim -0.5\text{‰}$ and under limited conditions (fixed CO_2), CO_2 is rapidly consumed, reducing $p\text{CO}_2$ levels to below equilibrium with the atmosphere and increasing the $\delta^{13}\text{C}_{\text{DIC}}$ of waters to $\sim -8\text{‰}$ (upper left of Figure 5-20). Under open conditions, such as would exist in productive soils, equilibrium with soil $p\text{CO}_2$ would produce waters with $p\text{CO}_2$ higher than atmospheric equilibrium. This would be exacerbated if calcite saturation were reached. These waters are located in the right side of the “carbonate weathering” box of Figure 5-20. The mixing of waters controlled by carbonate weathering and waters controlled by silicate weathering, such as is the case for the downstream stretches of the Ottawa River, produces waters with $\delta^{13}\text{C}_{\text{DIC}}$ of $\sim -11\text{‰}$ and high $p\text{CO}_2$ (centre-right of Figure 5-20). The $\delta^{13}\text{C}_{\text{DIC}}$ values are closer to that of “carbonate” waters because of the greater flux of DIC from those waters. The high $p\text{CO}_2$ results from lowering the pH by mixing low pH waters of the uplands with high pH, high DIC waters of the lowlands. The direction of shifts caused by in-river photosynthesis and respiration are also

shown on the plot, although, as already discussed, there is no evidence to suggest that these processes affect the $p\text{CO}_2$ or the $\delta^{13}\text{C}_{\text{DIC}}$ signals to a large degree.

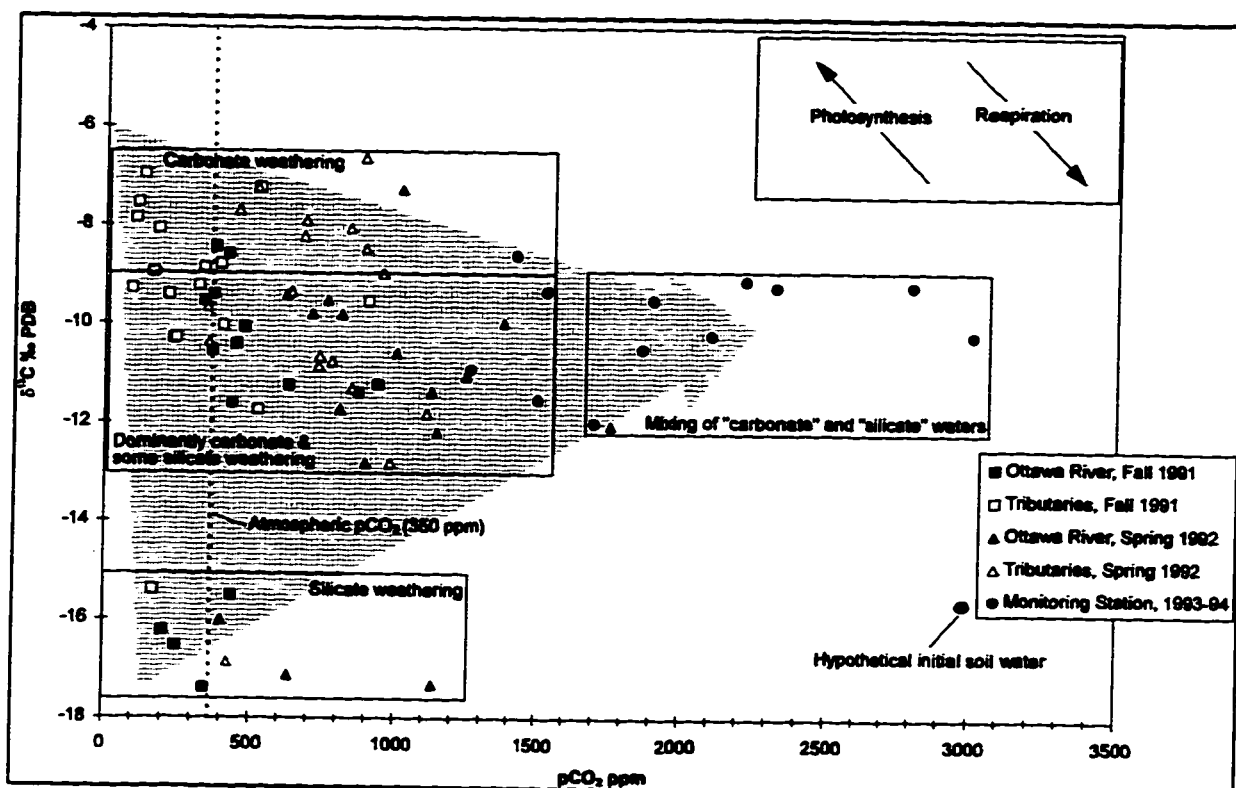


Figure 5-20: $\delta^{13}\text{C}_{\text{DIC}}$ versus $p\text{CO}_2$ for the Ottawa River and its tributaries and pathways for the conversion of soil water into river water.

5.3.6d $p\text{CO}_2$ of soil gas

The $p\text{CO}_2$ of a hypothetical soil atmosphere that must have been in equilibrium with soil water to produce observed carbon chemistry of river water can be calculated from $\delta^{13}\text{C}_{\text{DIC}}$ and DIC if we assume that: (1) in-river photosynthesis and respiration are insignificant. Previous arguments suggest this is reasonable; (2) carbonate precipitation is not a major carbon sink. Only a few tributaries are weakly calcite oversaturated and this state is usually seasonal, suggesting this assumption is reasonable. If calcite precipitation were a major sink for riverine carbon, the calculated $p\text{CO}_2$ would be undervalued; (3) exchange of CO_2 with the atmosphere is minimal. The lack of an atmospheric $\delta^{13}\text{C}$ signal in the carbon isotope data

suggest that this is the case. Evasion to the atmosphere will be discussed further in section 5.3.6e; (4) as calculated in section 5.3.2 the $\delta^{13}\text{C}_{\text{DIC}}$ of average soil water is -16‰; and 5) as discussed in section 5.3.5 the $\delta^{13}\text{C}_{\text{DIC}}$ contributed from carbonates is -0.5‰. The expressions for the pCO_2 of the hypothetical soil atmosphere are:

$$H_2CO_{3(\text{biological})} = \text{DIC} \cdot \left(\frac{\delta^{13}\text{C}_{\text{DIC}}}{\delta^{13}\text{C}_{\text{carb}} + \delta^{13}\text{C}_{\text{resp}}} \right) \quad \text{Equation 5-15}$$

$$\text{pCO}_{2(\text{soil})} = \frac{H_2CO_{3(\text{biological})}}{K_{\text{CO}_2}} \quad \text{Equation 5-16}$$

where $\delta^{13}\text{C}_{\text{DIC}}$ and DIC is the value measured in the river; $\delta^{13}\text{C}_{\text{carb}}$ is the value of $\delta^{13}\text{C}_{\text{DIC}}$ contributed from carbonate weathering; $\delta^{13}\text{C}_{\text{resp}}$ is the value of $\delta^{13}\text{C}_{\text{DIC}}$ contributed from respiration of organic material; and $H_2CO_{3(\text{biological})}$ is the carbonic acid calculated to have originated from biological carbon. Equation 5-16 converts the carbonic acid originating from biological material to the pCO_2 of the soil atmosphere (hypothetical) which must have been present to provide sufficient CO_2 to produce the observed river waters. Table 5-3 lists the hypothetical soil pCO_2 for the tributary basins and the Ottawa River basin. The average for lowland carbonate catchments, upland silicate catchments, and mixed catchments is $10^{-1.5}$, $10^{-2.85}$, and $10^{-2.3}$ ppm, respectively. As expected, the upland silicate basins which have only sparse soils have low soil pCO_2 while the lowland basins and their well developed soils generate relatively high soil pCO_2 , the mixed basins fall in-between. In reality it is likely that the existing soils in the upland basins have higher pCO_2 than that listed in Table 5-3 but inputs from such soils are diluted by soil poor or soil absent areas. The same is likely true for the lowland and mixed basins but to a lesser degree.

Basin	pCO ₂ ppm
<i>Ottawa River</i>	<i>7769</i>
Carnachigama	1108
Kenojevis	6186
Blanche	12371
Montreal	4561
Kipewa	722
Mattawa	2296
Petawawa	3036
Dumoine	1559
Noire	2846
Coulange	1842
Bonnechere	16855
Madawaska	8930
Mississippi	18892
Rideau	23864
Gatineau	1758
Rivière du Lièvre	4704
Petite Nation	6235
South Nation	42728
Rouge	2557
Nord	16167
Rigaud	52128

Table 5-3: Hypothetical pCO₂ of soil atmosphere for the Ottawa River basin and its tributary subbasins.

Using the data from Table 5-3 as a guide for soil conditions and equations 5-6, 5-7, and 5-8, DIC speciation and concentration in the hydrologic cycle, from rain water to river water, can be modelled using the following boundary conditions: (1) in the soil zone, DIC is proportional to pCO₂; (2) for carbonate weathering, DIC at calcite saturation = 2DIC in initial soil water (DIC_{calcite saturation} = 2DIC_{soil atmosphere}); (3) for silicate weathering, total DIC = DIC in initial soil water (DIC_{total} = DIC_{soil atmosphere}). The relationship between pCO₂, pH, and calcite saturation was calculated from the following equation:

$$a_{H^+}^3 = \frac{K_2 \cdot K_1^2 \cdot K_{CO_2}^2 \cdot pCO_2^2}{2K_{cal}} \quad \text{Equation 5-17}$$

where K_{cal} is the equilibrium constant for calcite dissolution and all other terms are as in equations 5-6, 5-7, 5-8. Activity coefficients for all species were assumed to be 1 so that Debye-Huckel considerations were avoided. This is a reasonable assumption for dilute waters. Figures 5-21 and 5-22 show the results of the model plotted on modified Bjerrum plots along

with the Ottawa River basin data. Almost all of the data can be explained by the three endmember curves suggesting that the estimates for the $p\text{CO}_2$ of the hypothetical soil atmosphere based on $\delta^{13}\text{C}_{\text{DIC}}$ are reliable. The estimates fall well within the range documented in the literature (Reardon et al., 1979; Aravena et al., 1992; Schiff et al., 1990; Stumm and Morgan, 1996; Drever, 1988).

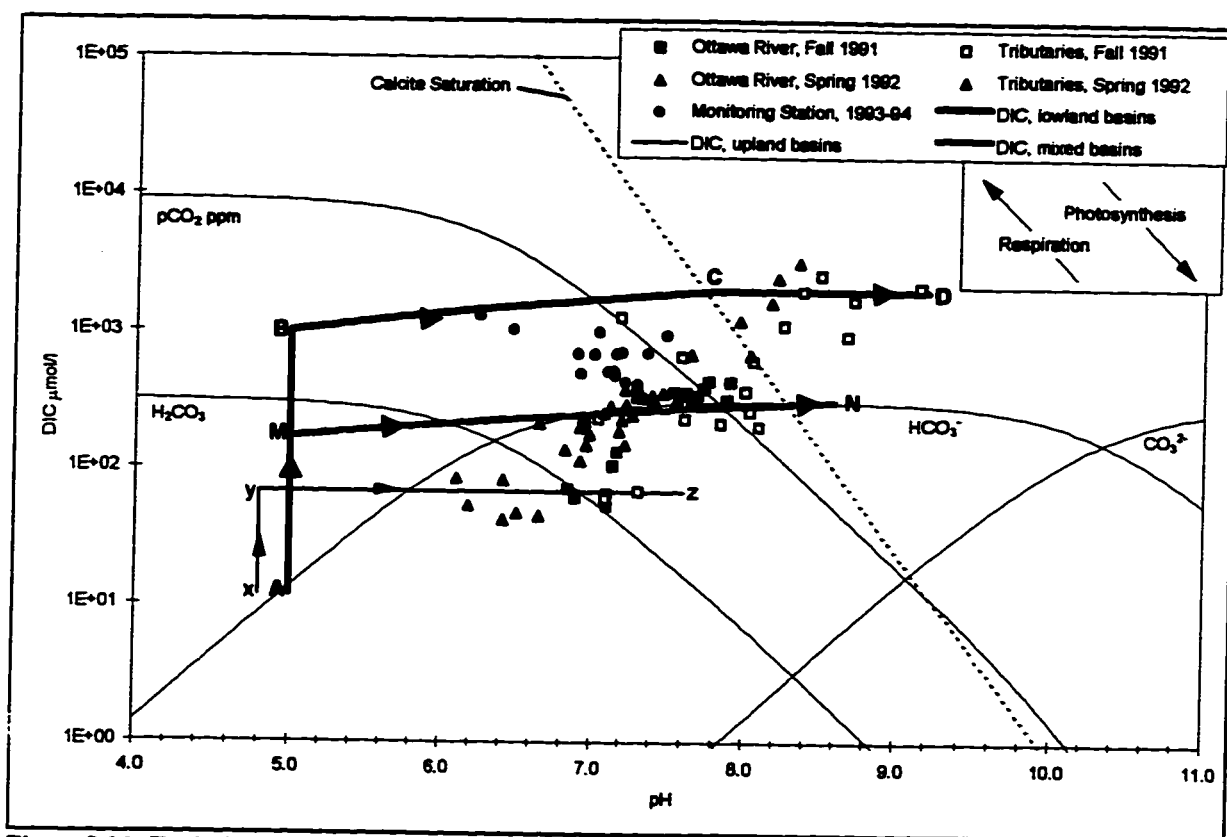


Figure 5-21: Evolution of dissolved inorganic carbon for hypothetical average water from (A) rain water to (B) soil water to (C) calcite saturation and toward (D) river water for weathering in lowland carbonate catchments; from (A) rain water to (M) soil water and towards (N) river water for weathering in mixed silicate/carbonate catchments; and from (x) rain water to (y) soil water and towards (z) river water for upland silicate catchments. Dissolved inorganic carbon species lines are for $\text{DIC} = 10^{-3.5} \text{ mol/l}$.

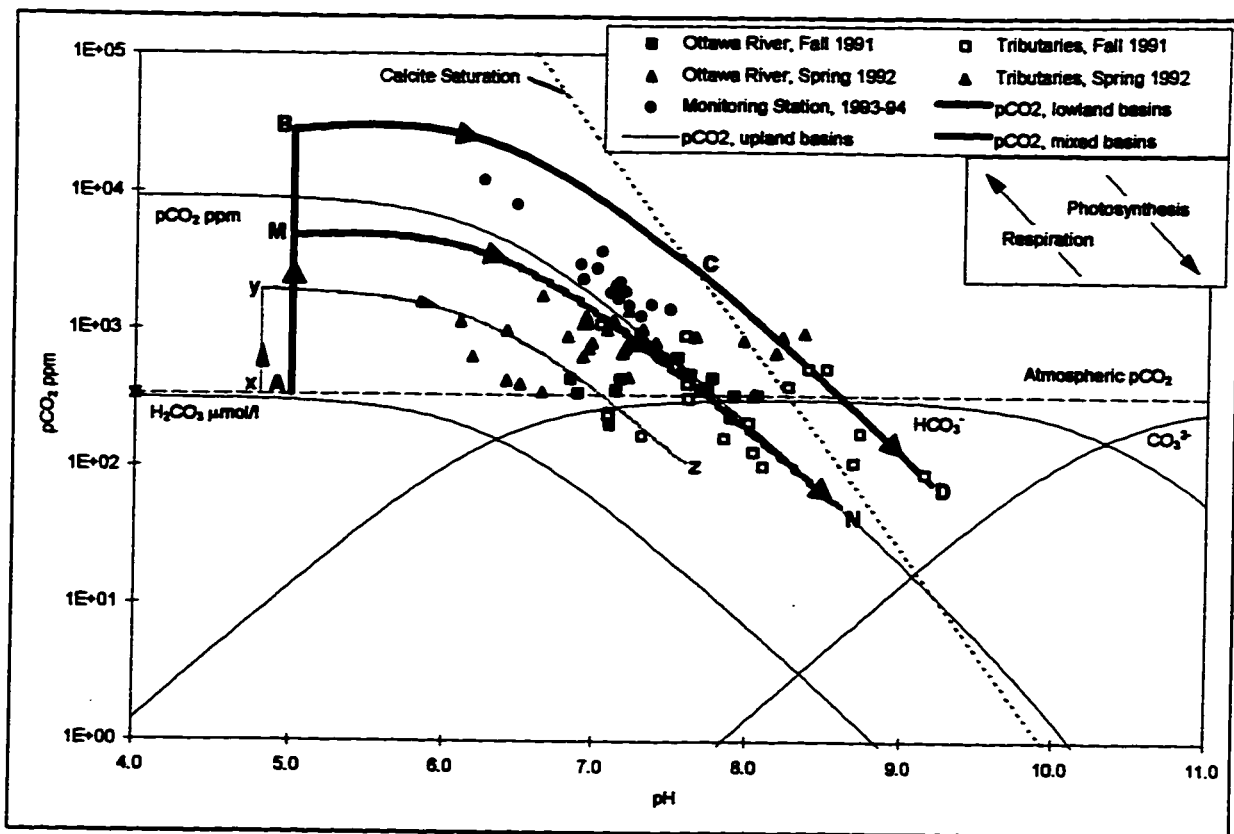


Figure 5-22: Evolution of $p\text{CO}_2$ for hypothetical average water from (A) rain water to (B) soil water to (C) calcite saturation and toward (D) river water for weathering in lowland carbonate catchments; from (A) rain water to (M) soil water and towards (N) river water for weathering in mixed silicate/carbonate catchments; and from (x) rain water to (y) soil water and towards (z) river water for upland silicate catchments. Dissolved inorganic carbon species lines are for $\text{DIC} = 10^{-3.5} \text{ mol/L}$.

5.3.6e Atmospheric Evasion

Riverine DIC losses can occur by CO_2 evasion to the atmosphere, CO_2 uptake by aquatic plants, and precipitation of carbonate minerals. As discussed previously, any signals caused by CO_2 consumption by aquatic plants are undetectable and the Ottawa River remains calcite undersaturated year round (appendix A, Table A2) leaving evasion to the atmosphere as the only possible sink term.

According to Mook (1970) up to six months are required for some lakes to reach isotopic equilibrium with the atmosphere. Yang et al. (1996) found that Lake Ontario and the main channel of the St. Lawrence River were roughly in isotopic equilibrium with the

atmosphere owing to the long residence time (~100 years) of water in the Great Lakes where the majority of St. Lawrence water originates. There are no estimates of mean residence time for water in the Ottawa River but dye tracer studies (Merritt, 1964) and a tritium spill at the Chalk River nuclear research facility (Natural Resources Canada Sitting Task Force, 1994) document peak concentrations of dye and tritium at Cheneaux station, 110km downriver of the injection, after roughly 10 days, a rate of 11km/day. The Ottawa River widens to a lake-like 2.5km width through much of this section and water movement rates are thus likely much slower through this section than through the remainder of the river. If we assume an average water movement rate of 15km/day then water originating in the headwaters (1000km from the mouth) would leave the basin in roughly 2-3 months. Distances from the headwaters of most tributaries to the mouth of the Ottawa River are also roughly 1000km and so the same residence time is applicable to them. 2-3 months is a maximum since only a small fraction of the water in the Ottawa River and its tributaries originates in their headwaters. It should be, however, noted that the estimate does not consider the effect of lakes or reservoirs. 2-3 months is less time than the Mook estimate for atmospheric isotopic equilibration. The carbon isotopes bear this out. Shifts toward heavy $\delta^{13}\text{C}_{\text{DIC}}$ beyond values attainable by carbonate weathering are not evident. Further, the dilute upland streams with low DIC and relatively low pCO_2 (less than atmospheric in a few cases) have purely respiration based carbon isotope values (-17‰). Clearly, isotopic equilibrium with the atmosphere is not attained in the waters of the Ottawa River basin. This suggests that CO_2 influxes from the atmosphere are insignificant but does not constrain CO_2 outfluxes from the river to the atmosphere.

Some attempts at calculating fluxes of CO₂ from rivers to the atmosphere exist in the literature. For the Rhine River, between 1963-1978, the mean pCO₂ and net flux of CO₂ was estimated to be 3300ppm and 9.16x10⁹mol/a, respectively (Kempe, 1982). In 1976-77, pCO₂ values of 4000ppm and a net flux of 1.5x10¹¹mol/a were estimated for the Amazon River (Stallard, 1980). Yang et al. (1996) found that pCO₂ and CO₂ fluxes in the St. Lawrence River fluctuated from 576 to 207 ppm and 10⁸ and -4x10⁷ mol/day in the spring and fall, respectively, and that this essentially mimics biologically controlled pCO₂ conditions and fluctuations in the epilimnion water of the Great Lakes. Note that the fall term is negative indicating an influx from the atmosphere to the river. These calculations are based on a theoretical diffusion model of the CO₂ flux between river and atmosphere and can be calculated from the following formula (Broecker, 1974):

$$F = D(C_{air} - C_{water}) / Z \quad \text{Equation 5-18}$$

where ($C_{air} - C_{water}$) is the concentration difference of gas between the overlying air and the bulk of the water, D is the gas- and temperature-specific diffusion coefficient, and Z is the thickness of the boundary layer: a thin film existing at the air-water interface. Z depends largely on wind speed (Broecker et al., 1978) and water turbulence (Holley, 1977) and ranges from 3x10⁻⁵m for the world ocean to 2x10⁻⁴m for small fresh water lakes. D/Z, therefore is the gas exchange rate, which gives the height of a water column which will equilibrate with the atmosphere per unit time (e.g. m/day). Z for the Ottawa River is estimated to be 10⁻⁴m, in-between the quiescent environment of a small fresh water lake and that of the world ocean, and D is 10⁻⁴m²/day at 10°C (Kempe, 1982) yielding a gas exchange rate D/Z of 1m/day. Depths of the Ottawa River range from 10m to 50m with the average roughly 13m (Natural Resources Canada Sitting Task Force, 1994). Accordingly, the Ottawa River would need 13

days to equilibrate with the atmosphere. Perhaps constant inputs of baseflow prevent this from happening. Using a D/Z of 100cm/day, C_{air} of 350ppm (1.60×10^{-8} mol CO_2/cm^3) and a mean $p\text{CO}_2$ of the Ottawa River over its length (C_{water}) of 1200ppm (5.49×10^{-8} mol CO_2/cm^3), the calculated flux of CO_2 from the Ottawa River to the atmosphere is 3.89×10^{-6} mol/ cm^2 day or 14.2mol/ m^2 a. If the surface area of the Ottawa River and its tributaries were known, a flux could be calculated. This information could be easily produced using satellite imagery. If we estimate the river to be 400m wide and 1100km long then the annual CO_2 evasion would be 6.2×10^9 molC. Evasion from the tributaries would likely be as large making the CO_2 evasion from both sources $\sim 1.3 \times 10^{10}$ molC/a.

Considering the many assumptions needed to arrive at this figure (for example, the $p\text{CO}_2$ at the mouth of the Ottawa River varies by an order of magnitude from 1200 to 12,000 ppm and so arriving at a reliable average $p\text{CO}_2$ for the entire length of the river is prone to error), it can represent only a hunch for the order of magnitude of evasion. CO_2 evasion from some of the lowland tributaries may be the process that causes them to be calcite oversaturated, although photosynthetic CO_2 consumption could also be the cause.

5.3.6f Riverine Flux

The flux of DIC along the length of the Ottawa River and for its tributaries for the spring and fall is shown in Figure 5-23. The flux from the lowland basins is dominant in the spring, with the South Nation River contributing the most. In the fall the Rivière Gatineau is the major contributor. This is purely a consequence of hydrology where the flow of the Rivière Gatineau is much less variable than flows from the lowland rivers, such as the South Nation and Rideau Rivers, and thus provides the lion's share of the discharge in the fall. As

discussed in section 5.3.4, this annual hydrological pattern is the primary process responsible for elevated concentrations of DIC and other major ions at the mouth of the Ottawa River in the spring and fall.

The average flux of DIC from the mouth of the Ottawa River is 1373 mol/s or 4.33×10^{10} mol/a. This represents 0.13% of the annual global DIC flux from rivers of 3.25×10^{13} mol (Berner and Berner, 1996) and 11% of the annual DIC flux of the St. Lawrence River of 3.9×10^{11} molC (Yang et al., 1996) into which the Ottawa River flows.

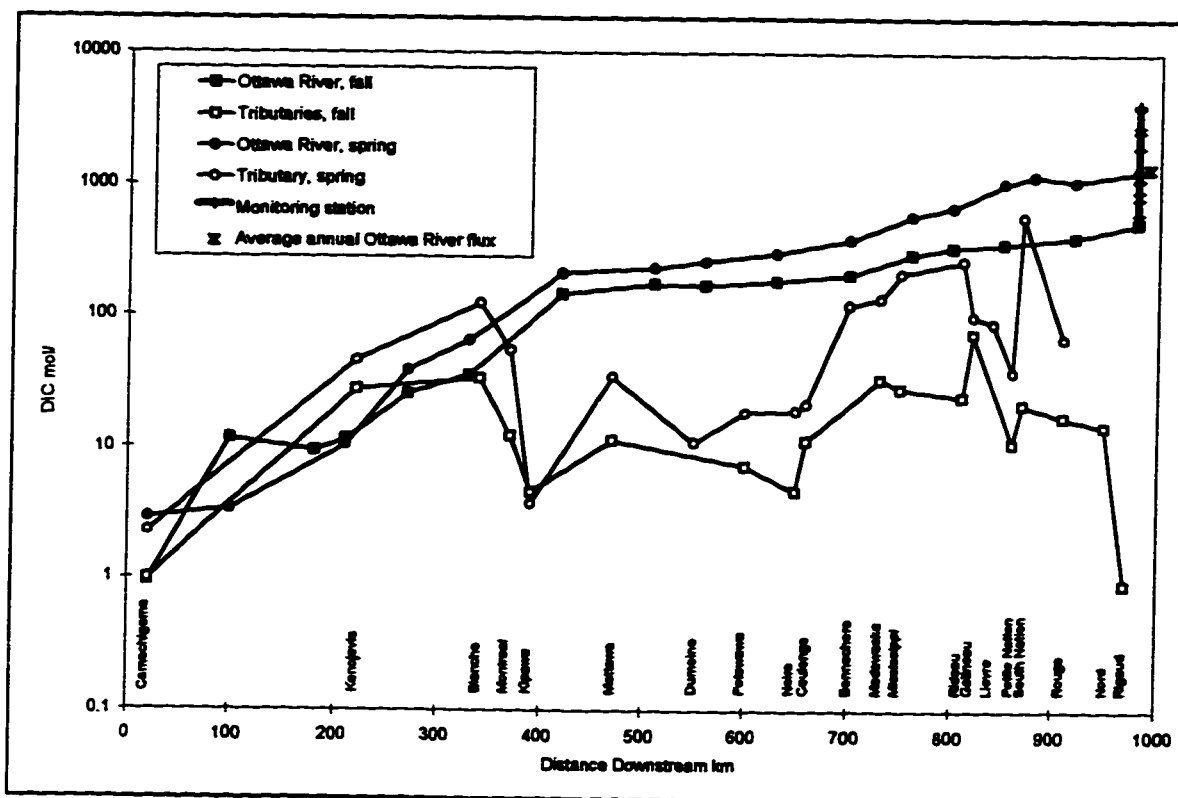


Figure 5-23: Flux of DIC from the Ottawa River and its tributaries.

5.3.6g Riverine Sources

The numerator of equation 5-15 calculates the concentrations of DIC attributable to respiration and to carbonate dissolution. For the Ottawa River, this amounts to 61% or 2.65×10^{10} molC/a and 39% or 1.68×10^{10} molC/a for respiration and carbonate dissolution,

respectively. If we crudely assume that the average respiration rate for the whole basin is $0.5 \text{ mmolC/m}^2/\text{hr}$, based on the data published Cerling et al. (1991), then total annual respiration for the Ottawa River basin with an area of $149,000 \text{ km}^2$ will be $6.5 \times 10^{11} \text{ molC/a}$. This means that the river transports 6.6% of respired carbon from the basin, the remainder diffusing directly to the atmosphere from the soil. If the CO_2 which evades to the atmosphere from the surface of the river and its tributaries is included, the estimate becomes 8.6%. Obviously, the accuracy of this estimate relies strongly on the accuracy of the estimate for the rate of respiration for the basin. The rate assumed here is based on research conducted in Utah and Nevada and must therefore be considered a first-order approximation only.

5.3.6h pCO_2 Trends in Major Rivers

Studies of DIC in some major rivers, such as the Amazon, Changjiang (Yangtze), Orinoco, Rhine, and Fraser show that the pCO_2 in these rivers is about 10-15 times that expected for equilibrium with the atmosphere and that these high values are typically reached in the downstream reaches (Stallard, 1980; Devol et al., 1987; Richey et al., 1988, 1990; Gao and Kempe, 1987; Depetris and Paolini, 1991; Edmond et al., 1995; Kempe, 1982; Cameron et al., 1995). The isotopic values of the DIC in these rivers suggest that the CO_2 overpressures originate to a considerable degree from the oxidation of organic matter (Richey et al., 1988) and in some cases nutrient pollution was assumed to have been the prime cause of enhanced organic activity leading to these signatures (Buhl et al., 1991). However, it is more plausible that the dominant control on pCO_2 (and the speciation of carbon) in rivers, is the level of soil respiration and the rate of chemical weathering of the substrate and that

fluctuations caused by in-river processes, such as photosynthesis and respiration, are secondary (e.g. Flinthrop et al., 1996).

Consider a hypothetical river basin of average gradient and with homogenous geology and climate. In the headwaters relief and physical weathering rates would be high, soil and vegetation would be poorly developed and immature, and there would therefore be an abundance of exposed fresh material available for weathering by the relatively low CO_2 production of the immature soils. Conversely, the lower reaches of the basin (floodplains) would be heavily weathered, relief would be low, physical weathering would be low, and soils and vegetation would be well established, producing an environment with relatively little fresh material available for weathering by the relatively large production of CO_2 from the mature forest. The weathering of fresh material in the headwaters would rapidly consume the available soil pCO_2 leaving the resulting stream waters relatively low in pCO_2 , whereas the dearth of weatherable material in the floodplains would leave lowland waters rich in pCO_2 , producing the observed downstream enrichment of pCO_2 recorded in the literature.

In real river basins, the distribution of lithologies and geological ages of the lithologies as well as geological history of the basin would cause secondary perturbations on this primary signal. For example, even for river basins such as that of the Ottawa River, which has recently undergone large environmental changes (Quaternary glaciation and marine incursion) and which contains easily weathered carbonate rocks in its floodplains - the opposite of the above described reduced downstream weatherability - the primary downstream pCO_2 enrichment signal is discernible (Figure 5-17).

5.4 ROCK WEATHERING

5.4.1 Potassium

Figures 5-24 and 5-25 illustrate the downstream trend of K^+ for the Ottawa River and its tributaries in the spring and fall. The data used in Figure 5-25 come from Environment Canada's (1993) Envirodat database and is averaged over 1978-88. Its main purpose here is to corroborate the data from this study. The two datasets agree strongly.

K^+ in global river water comes predominantly from the weathering of silicate minerals, mainly potassium feldspar (orthoclase to microcline) and mica (biotite and muscovite), and secondly from cyclic salts and K^+ fertilizers (Berner and Berner, 1996; Drever, 1988; Meybeck, 1987). In the Ottawa River basin, roughly 20-30% of the observed K^+ in river water can be explained by precipitation input (see Table 5-1), the remainder therefore comes from silicate weathering or pollution (K^+ fertilizers). Unfortunately, it is difficult to differentiate between K^+ from silicate weathering and K^+ from fertilizers. Spatially, the tributary basins containing the highest percentage of agricultural land use, the South Nation, Rideau, Mississippi and Bonnechere, have the highest K^+ concentrations. However, they also drain the lowlands which contain very fine grained and immature silicate rich sediments deposited in the Champlain Sea as well as Paleozoic shales and sandstones. Meybeck estimates that 75% of silicate weathering based K^+ in rivers comes from the weathering of silicates in sedimentary rocks and 25% from igneous and metamorphic rocks. Natural sources of K^+ are therefore more abundant in the lowlands than the uplands, the former having thus higher K^+ values, making an estimate of pollutive K^+ difficult. There is no historical records of K^+ to establish a pre-fertilizer baseline.

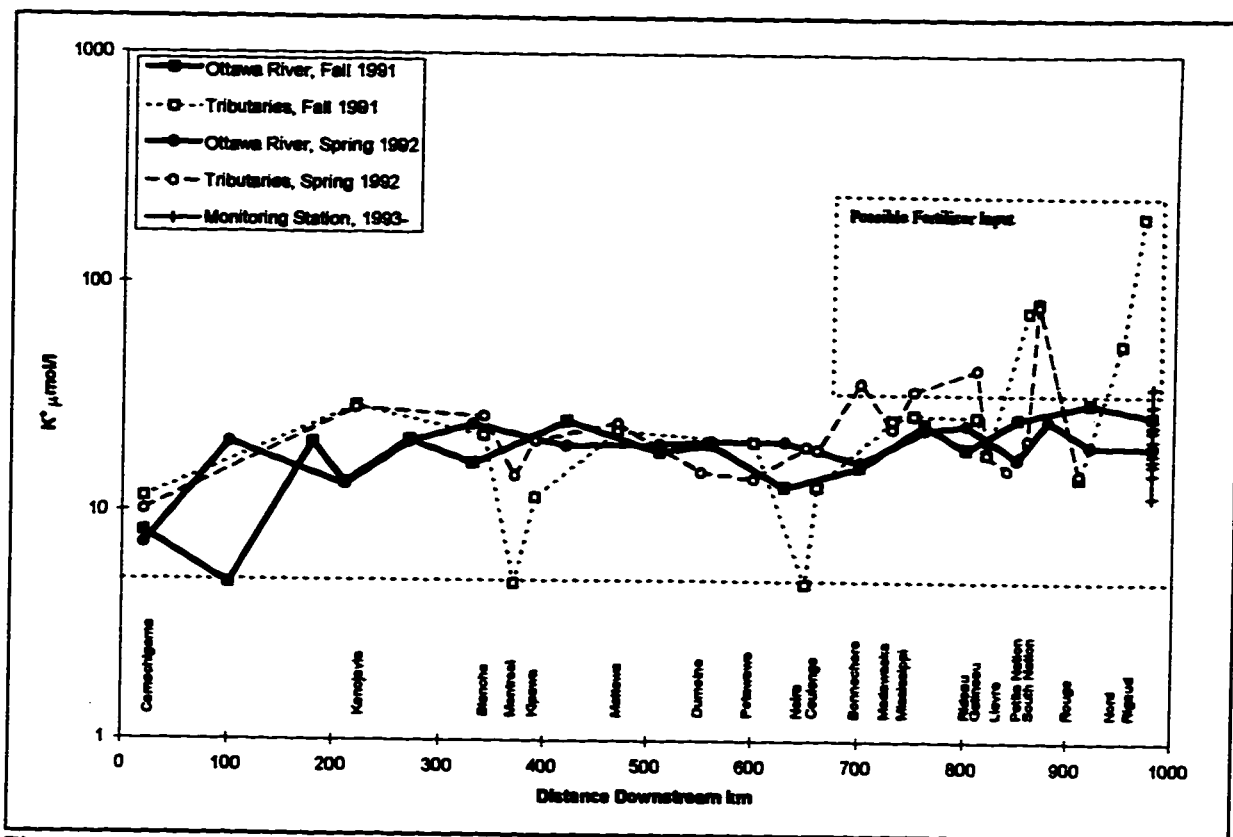


Figure 5-24: Downstream trend for potassium in the Ottawa River and its tributaries, data from this study.

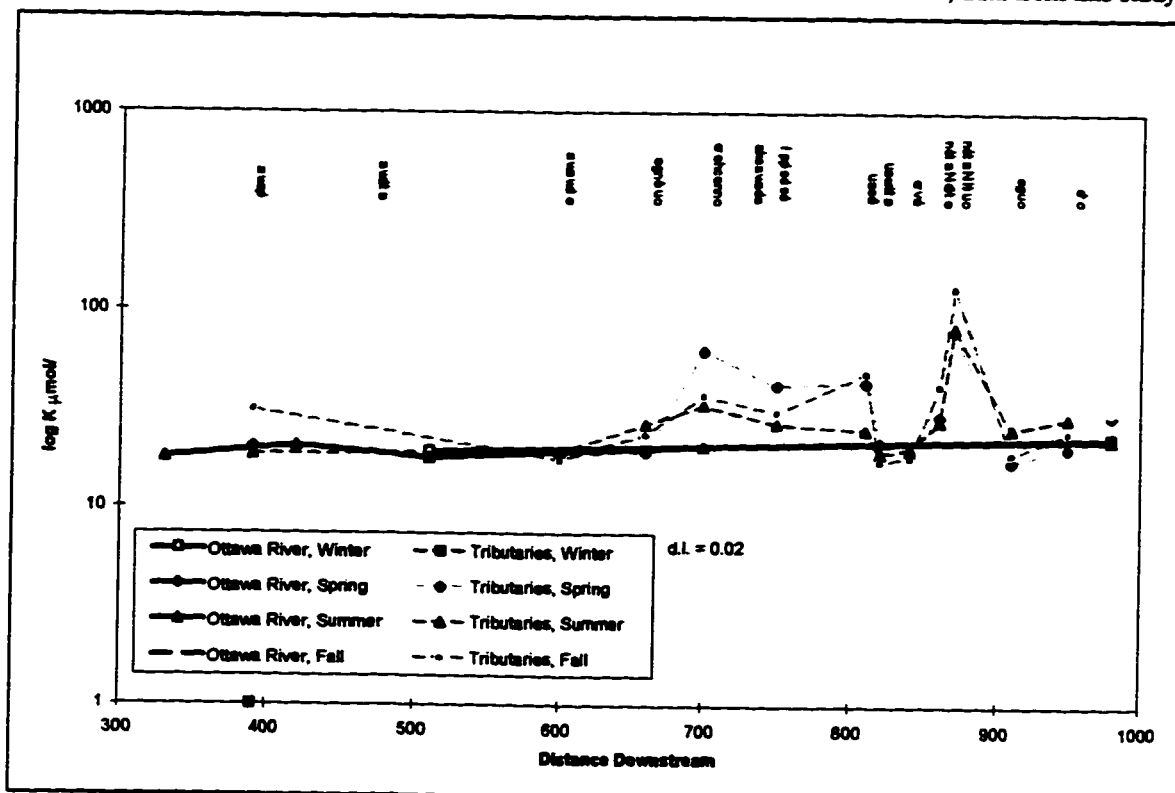


Figure 5-25: Downstream trend for potassium in the Ottawa River and its tributaries; data from Environment Canada (1993), 1979-82.

5.4.1a Equilibrium Stability Diagram

One technique to gain insight on the nature of weathering in a water-rock system is to plot the composition of waters on an equilibrium stability diagram. This is done by plotting the stability fields of various weathering products from thermodynamic data and the stoichiometry of reaction. For example, the equilibrium between kaolinite and gibbsite can be represented as:

$$\begin{aligned}
 & \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 + \text{H}_2\text{O} = \text{Al}(\text{OH})_3 + 2\text{H}_4\text{SiO}_4 \\
 & \log K = 2 \log a_{\text{H}_4\text{SiO}_4} = -\frac{\Delta G^\circ_f}{RT} = -8.4 \\
 & \therefore \log a_{\text{H}_4\text{SiO}_4} = -4.2
 \end{aligned}
 \tag{Equation 5-19}$$

where ΔG°_f is the Gibbs free energy of formation of the products minus the reactants, R is the gas constant, and T is the temperature in degrees Kelvin. The same can be done for the equilibrium between K-feldspar and kaolinite, producing the relationship $\log(a_{\text{K}^+}/a_{\text{H}^+}) = -4 \log a_{\text{H}_4\text{SiO}_4} - 9.1$ and for the equilibrium between other weathering products. For a detailed explanation of equilibrium stability diagrams, see Nesbitt (1984). Plotting waters on the resulting diagram shows with which weathering phase the waters are in equilibrium. Notably, the axis of the stability fields for each mineral are dependent on the thermodynamic data chosen to plot them. These data can vary considerably and so the boundaries between minerals should be viewed as approximate.

Figure 5-26 plots the waters of the Ottawa River basin on a mineral-solution equilibrium stability diagram for K^+ . Line A-F is a hypothetical path for the weathering of K-feldspar by rain water. Initially, K-feldspar would weather to gibbsite until enough silica was in solution for kaolinite to become stable at point B. Weathering of K-feldspar would continue along the line B-C until all gibbsite was consumed at point C, beyond which only kaolinite would form until the release of enough K^+ and silica produces a solution in equilibrium with

muscovite at point D. Eventually point F would be reached where no further weathering would take place and where both K-feldspar and muscovite would be stable. The majority of waters in the Ottawa River basin fall along the line B-C, suggesting that gibbsite and kaolinite are the clays most frequently produced by silicate weathering in the basin. Lowland tributaries draining the Leda clays (immature silicate/carbonate glacio-marine clays) have elevated K^+ concentrations relative to the upland tributaries causing them to have waters in equilibrium with muscovite. The elevated K^+ could be anthropogenic, from K-fertilizers, as these basins are farmed heavily or they could result from the abundance of unweathered silicate minerals and high rock/water ratios in the Leda clays. If the elevated K^+ concentrations were anthropogenic, it is interesting to consider whether agriculture could change the weathering products of a watershed. Other tributaries, draining at least some Paleozoic sediments, have both elevated K^+ and depleted silica concentrations. A large percentage of these catchments are underlain by carbonates. This can explain the depleted silica concentrations, but elevated K^+ concentrations in the absence of silica (H_4SiO_4) cannot be explained by rock weathering. If so, K-fertilizer input may indeed be a contributor of K^+ to the lowland agricultural tributaries.

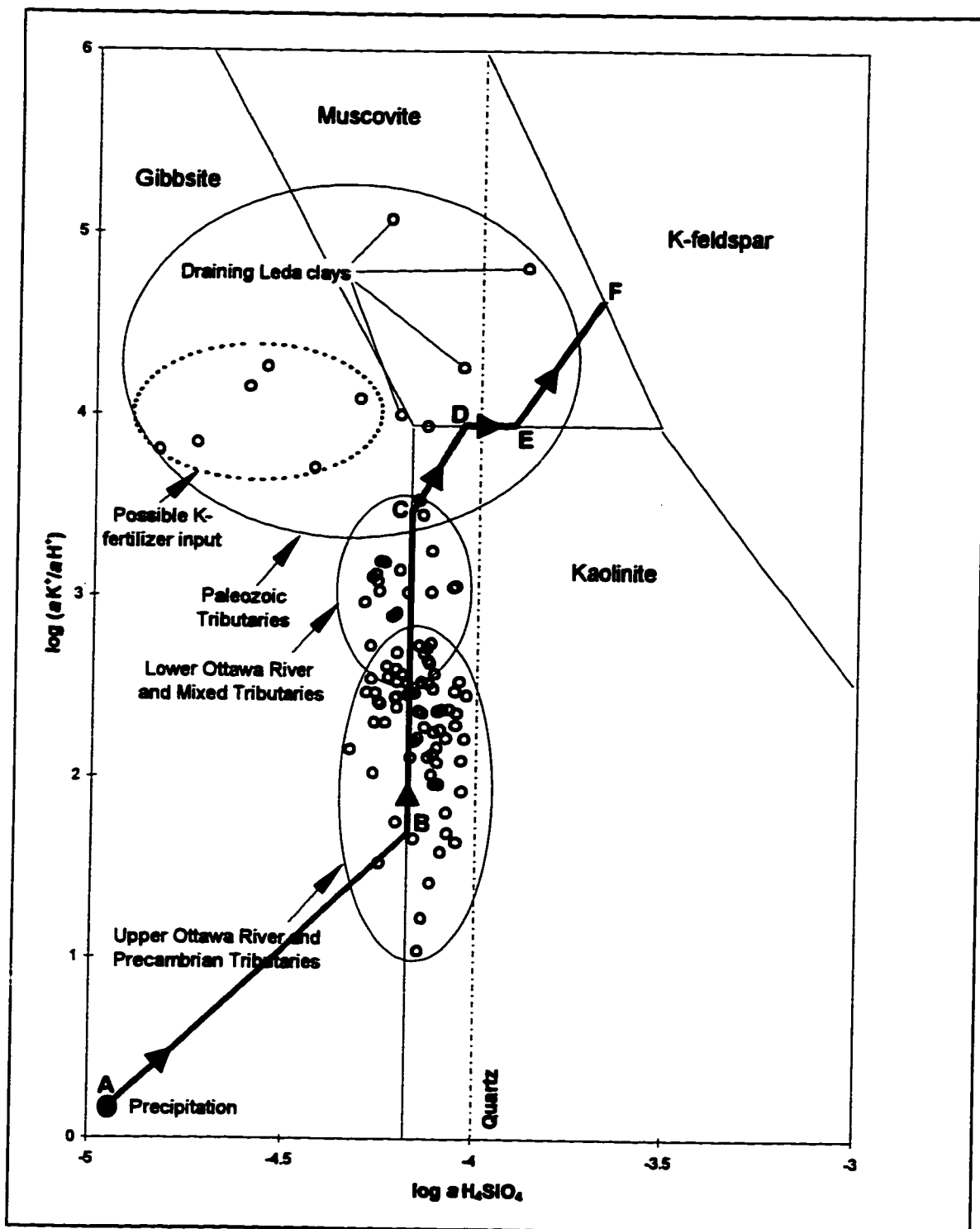


Figure 5-26: Equilibrium stability diagram for silicate minerals and solution at 25°C and 1 bar.

5.4.1b Temporal Distribution

Seasonally, K^+ behaves much like DIC. The K^+ rich lowland tributaries contribute a relatively greater flux of K^+ during the high water stands in the spring and fall and this is reflected by increased concentration at the mouth of the Ottawa River. Figure 5-27 illustrates this for the present data and Figure 5-28 for the 4 year average calculated from Envirodat (Environment Canada, 1993). The annual average for the same period, 1979-82, was relatively stable at $28.5 \mu\text{mol/l}$.

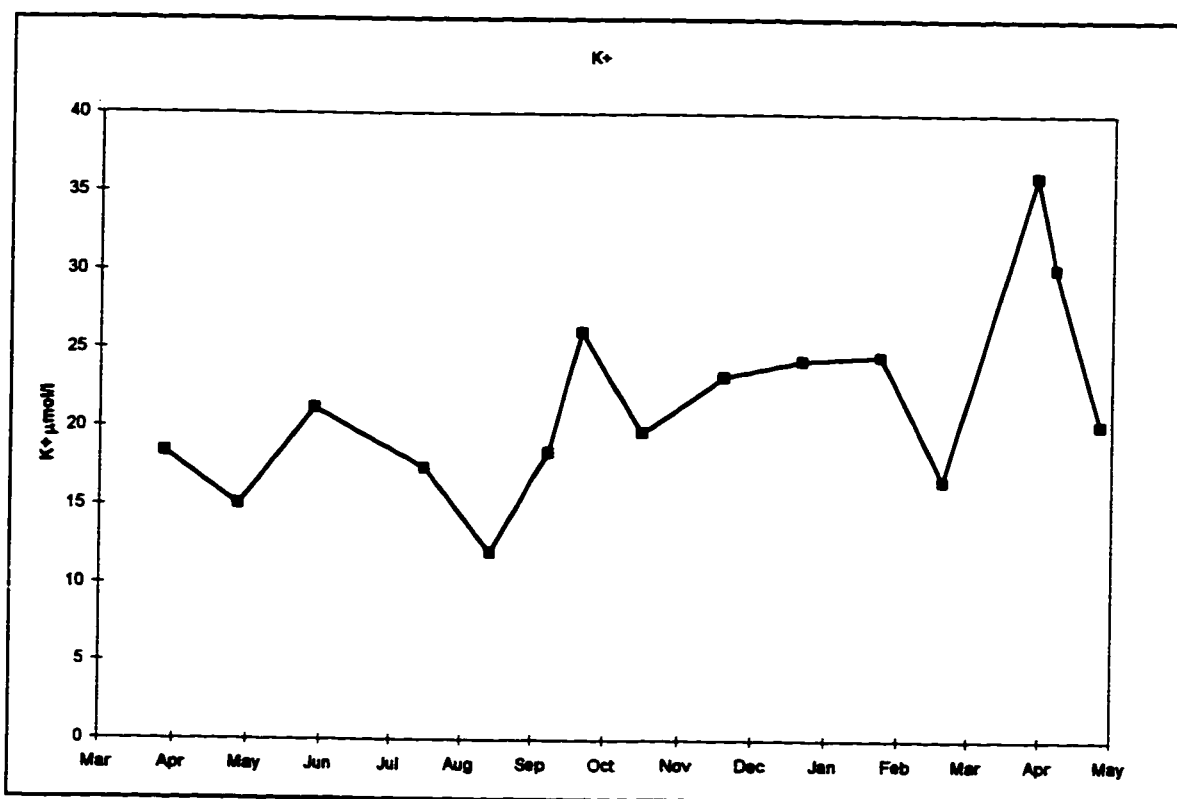


Figure 5-27: Monthly K^+ concentration at the mouth of the Ottawa River, 1993-94.

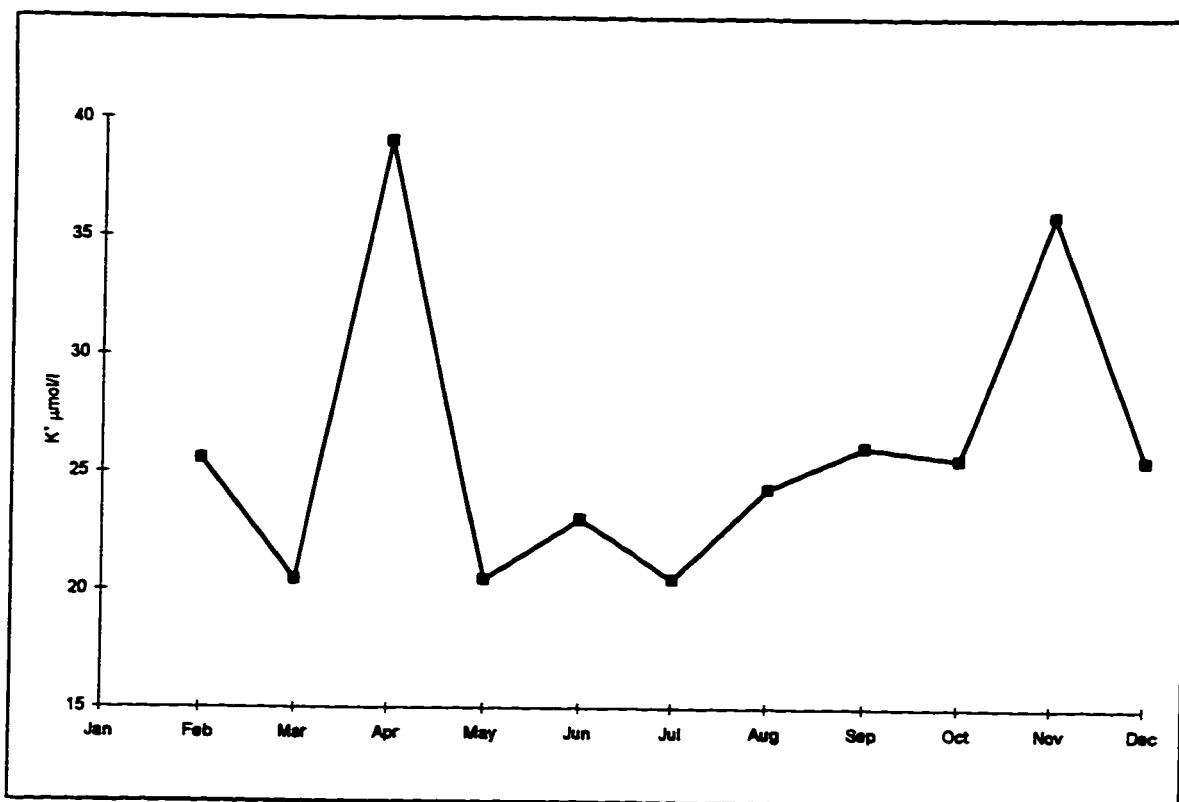


Figure 5-28: Monthly average K⁺ concentration, 1979-82, data from Environment Canada, 1993.

5.4.2 Calcium and Magnesium

The majority of Ca²⁺ and Mg²⁺ in river water in the Ottawa basin can be accounted for by either mineral weathering or by anthropogenic inputs, with less than 20% (and often less than 10%) coming from precipitation (Table 5-1). It follows that the concentration of these ions is primarily controlled by geology and human population and secondarily by climatic factors, such as annual precipitation, temperature, and evapotranspiration. Basins such as the South Nation River and Rivière Kipawa attest to this. The South Nation basin, with dominantly carbonate geology and high population density, receives less than 3% of its Mg²⁺ and Ca²⁺ load from precipitation despite its relatively high evapotranspiration rate of 60%. The Kipawa basin, on the other hand, is entirely underlain by chemically resistant gneissic granitoid rocks and is almost unpopulated. Consequently, the Kipawa River receives much

greater proportion of the above ions from precipitation, despite its having a lower annual evapotranspiration rate (44%). Note, however, that even in this case precipitation inputs do not exceed 30%, further illustrating the dominantly geogenic control for these cations.

5.4.2a Spatial Distribution

Figure 5-29 illustrates the downstream trend of Ca^{2+} for the Ottawa River and its tributaries for the fall and the spring of 1991-92. The trend for Mg^{2+} is essentially identical. Concentrations follow the abundance of carbonate rocks. In the headwaters, which are devoid of carbonates, Mg^{2+} and Ca^{2+} are derived primarily from the weathering of silicates such as Ca-plagioclase, pyroxenes, amphiboles and biotite. Weathering rates of silicates are slow and so the waters of the uplands are dilute. Downstream, where carbonates are present, Ca^{2+} and Mg^{2+} increase. Both the process of dilution and hysteresis are evident in the basin. In the lowlands, flow variation and chemical weathering rates are much higher and therefore concentrated residues easily accumulate during low flow periods and hysteresis controls the temporal concentration distribution. Concentrations of Ca^{2+} and Mg^{2+} are therefore higher in the spring than the fall in the lowland tributaries. In the uplands, where flows are less variable, and chemical weathering rates are lower due to the nature of the substrate, spring runoff causes dilution. As a result, concentrations of Ca^{2+} and Mg^{2+} are lower in the spring than the fall. This is the same pattern as that documented for DIC in section 5.3.4.

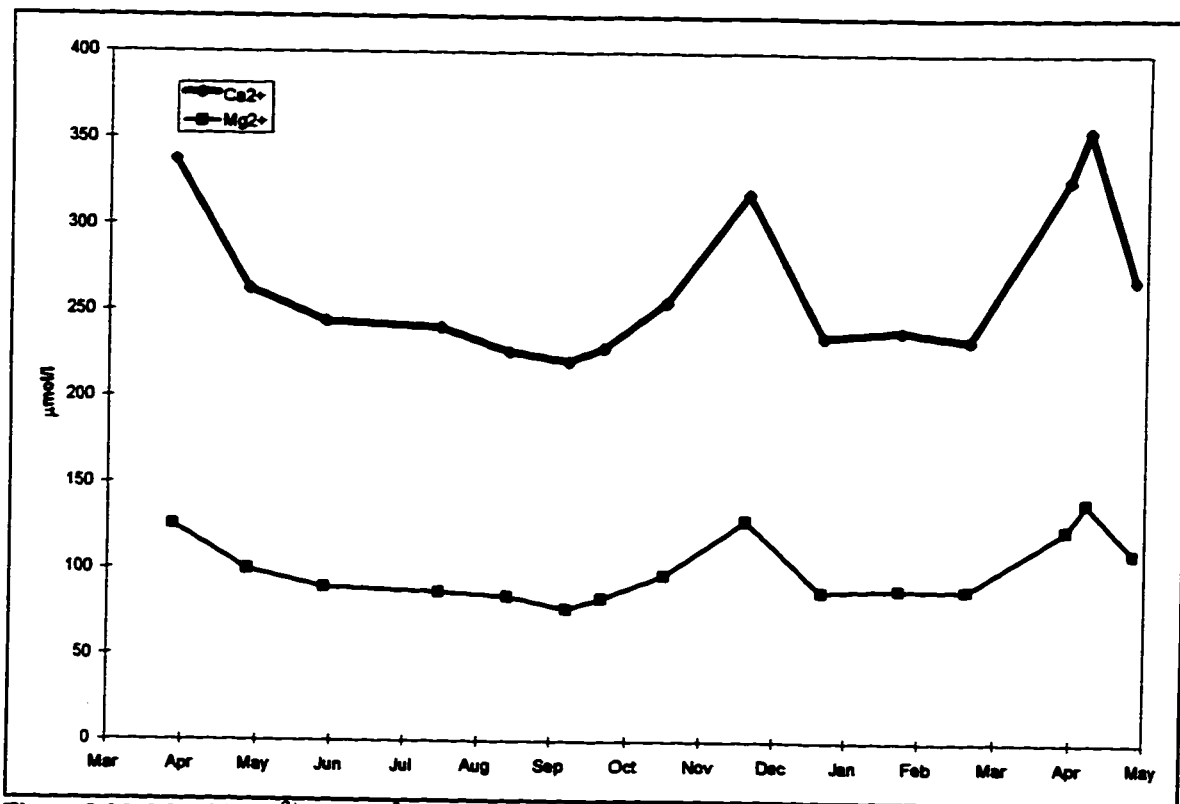


Figure 5-30: Monthly Ca^{2+} and Mg^{2+} concentrations at the mouth of the Ottawa River, data from this study, 1993-94.

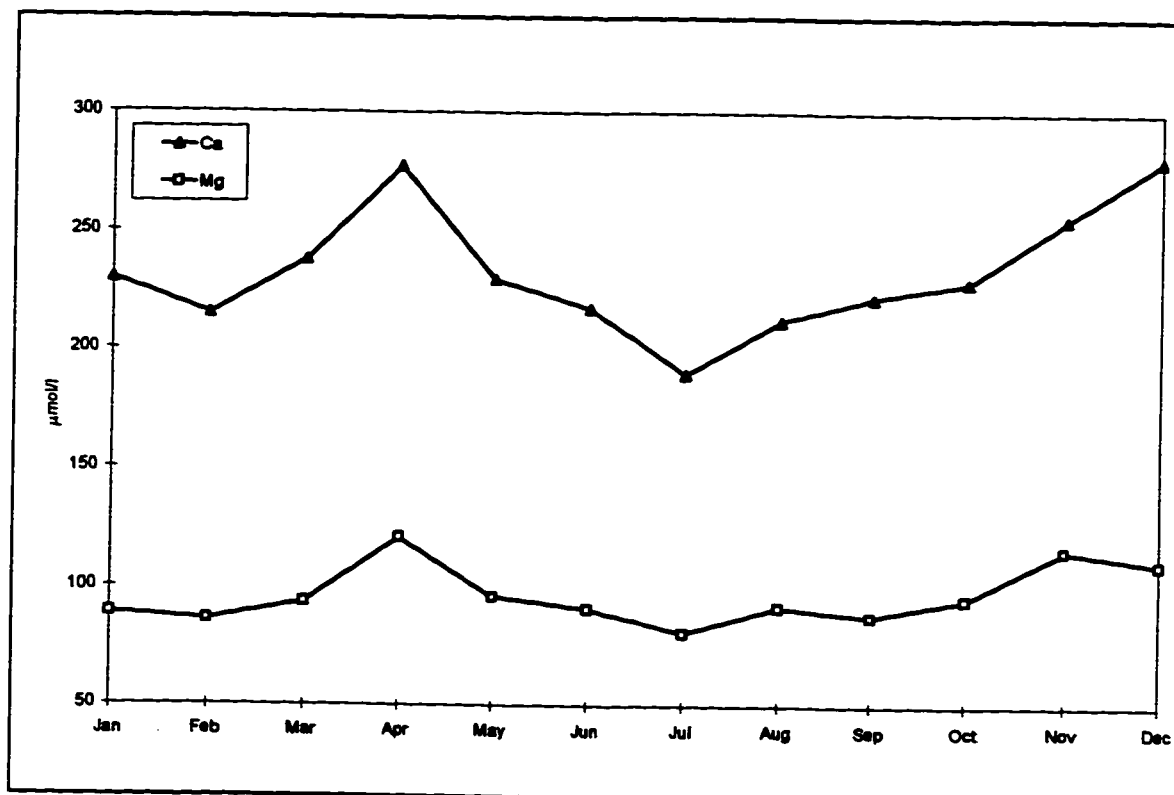


Figure 5-31: Average monthly Ca^{2+} and Mg^{2+} concentrations at the mouth of the Ottawa River, 1978-88; calculated from Environment Canada (1993).

5.4.2c Contributions from silicate and carbonate weathering

The amount of Ca^{2+} and Mg^{2+} generated from silicate weathering can be approximated using carbon isotopes. It was estimated in section 5.3.6e that 39% of the DIC for the Ottawa River could be attributed to C from carbonates. From the stoichiometry of carbonate dissolution, this implies that $0.39[\text{DIC}] = [\text{Ca}^{2+} + \text{Mg}^{2+}]$ contributed from carbonate weathering, where the square brackets denote concentration. Therefore, of the total $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ ($367\mu\text{mol/l}$) for average conditions at the mouth of the Ottawa River, $276.5\mu\text{mol/l}$ and $90.5\mu\text{mol/l}$ of $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ originate from carbonate and silicate weathering, respectively. This illustrates the dominance of carbonate weathering for the dissolved load. Separating the term $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ into its Ca^{2+} and Mg^{2+} components would require detailed information on the composition of carbonates in the basin.

5.4.2d Silicate Weathering Products

Gibbsite and kaolinite are the main products of silicate weathering in the basin, as shown by the mineral-solution equilibrium stability diagram for Ca^{2+} (Figure 5-32). This is particularly true for the dominantly silicate portions of the basin, the upper Ottawa River and Precambrian tributaries. Where carbonate rocks predominate, in basins draining Paleozoic rocks, and to a lesser degree in the mixed basins, silica concentrations are lower and only gibbsite is produced from silicate weathering. In contrast, for those tributaries draining the silicate rich Quaternary Leda clays of the Champlain Sea, silicate weathering can yield enough silica to stabilize kaolinite. The equilibrium stability diagram for Mg^{2+} is essentially identical to that of Ca^{2+} .

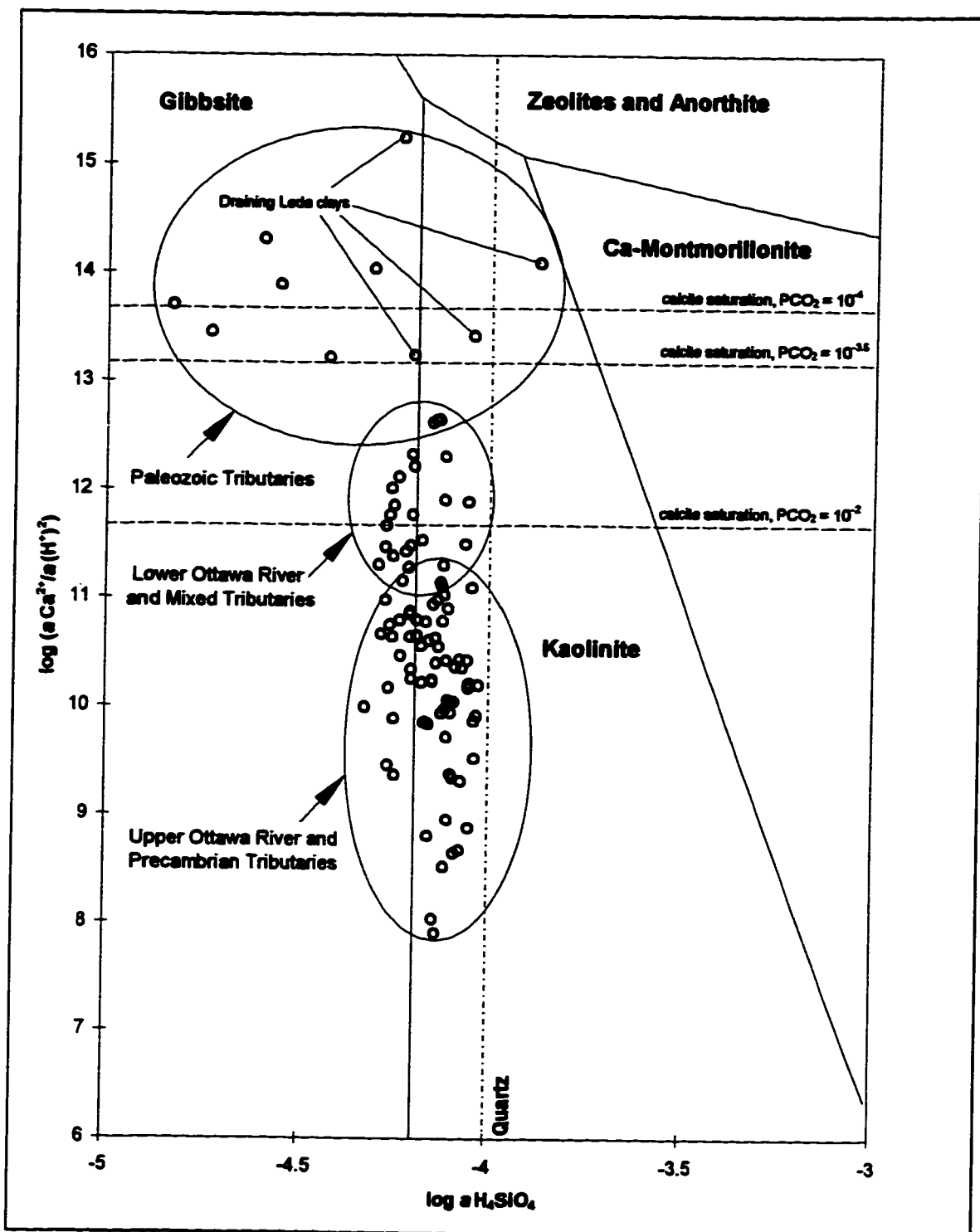


Figure 5-32: Ca^{2+} mineral-solution equilibrium stability diagram for the Ottawa River and its tributaries.

5.4.2e Riverine Flux

Figure 5-33 illustrates the flux of Ca^{2+} from the Ottawa River and its tributaries along the length of the river. Ca^{2+} behaves conservatively, showing no flux decreases along the river with the exception of the stretch between 400 and 500km which may be due to incomplete mixing of dilute tributaries. In a trend similar to that of DIC, the lowland tributaries dominate the Ca^{2+} flux in the spring, whereas the Rivière Gatineau is the dominant source in the fall owing to its steady baseflow. The largest single flux of Ca^{2+} comes from the South Nation River in the springtime. The average flux of Ca^{2+} from the Ottawa River basin is 536mol/s. Trends for Mg^{2+} are almost identical but values are roughly 1/3 those of Ca^{2+} . The average flux of Mg^{2+} from the Ottawa River basin is 200mol/s.

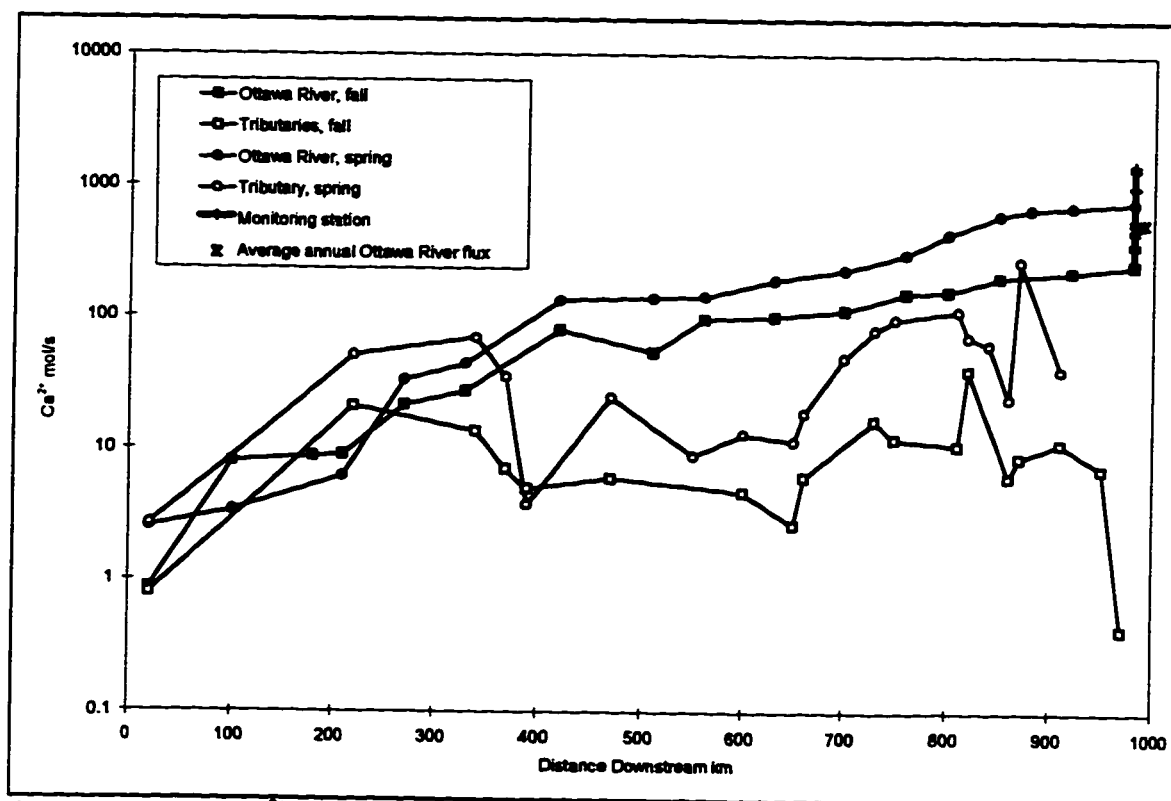


Figure 5-33: Flux of Ca^{2+} from the Ottawa River and its tributaries.

5.5 SULFATE AND ISOTOPES OF SULFUR

The natural sources of SO_4^{2-} in river water are cyclic salt in rainfall, ground water and weathering of the sulfur-rich minerals, pyrite, anhydrite and gypsum. Human activities (e.g. air pollution, mining, smelting of sulfidic ore, refining of petroleum, and chemical industries, such as the production of fertilizer with sulfuric acid) also contribute to the SO_4^{2-} content of river water. These multiple sources of sulfate can frequently be distinguished by their specific isotopic signatures. For example, river sulfate derived from dissolution of evaporites has positive $\delta^{34}\text{S}$ values whereas sulfate from the oxidation of sulfides or from biogenic emissions may have strongly negative $\delta^{34}\text{S}$. The latter is because sulfide minerals tend to be isotopically lighter than sulfate minerals, and hence the oxidation of sulfides (and that of organic sulfur) transposes the depleted $\delta^{34}\text{S}$ signal to sulfate products (Pearson and Rightmire, 1980).

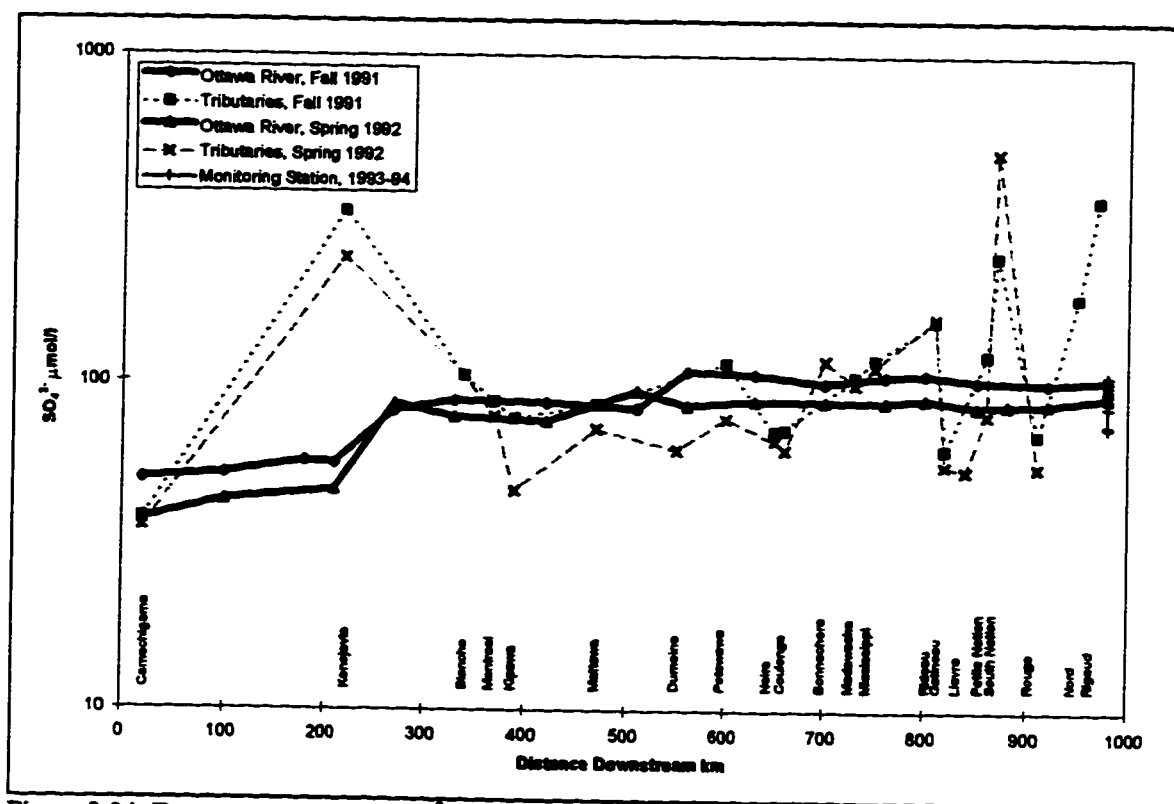


Figure 5-34: Downstream trend of SO_4^{2-} for the Ottawa River and its tributaries.

5.5.1a Spatial Distribution

The average sulfate concentrations in the Ottawa River increase from about $50\mu\text{mol/l}$ in the headwaters to $100\mu\text{mol/l}$ at the mouth (Figure 5-34). 90% of this can be attributed to atmospheric input (Table 5-1). The average sulfate flux at the mouth of the river is calculated to be 182mol/s (Figure 5-35) or $5.75 \times 10^9 \text{mol/a}$. According to Ivanov (1983), the annual SO_4^{2-} flux from continents to oceans is $6.78 \times 10^{12} \text{mol/a}$ of S, with contributions from rivers, anthropogenic emissions and ground water of 48, 48 and 4%, respectively. The Ottawa River, therefore, accounts for 0.18% of the riverine and 0.09% of the total S flux. This agrees with the estimates of Yang et al. (1996) that the Ottawa River provides 6% of the St. Lawrence SO_4^{2-} budget.

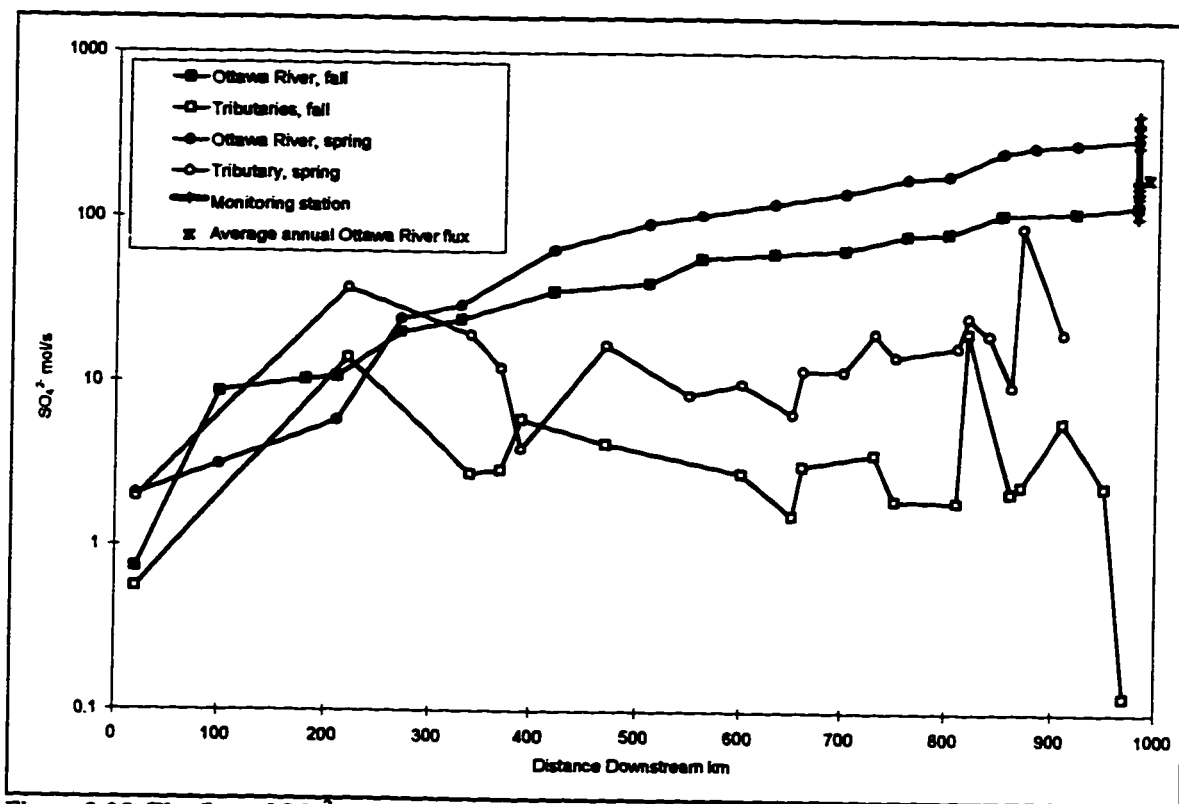


Figure 5-35: The flux of SO_4^{2-} from the Ottawa River and its tributaries.

The $\delta^{34}\text{S}$ of sulfate in the Ottawa River (3.3 to 5.9‰, Figure 5-36) is comparable to that of precipitation (+3 to +5‰) and soil water (+3 to +6‰) in central and southern Ontario (Nriagu and Coker, 1978; Van Stempvoort et al., 1991; Van Stempvoort et al., 1992). The SO_4^{2-} concentrations in local rain are about $47 \pm 42 \mu\text{mol/l}$, in throughfall $58 \pm 39 \mu\text{mol/l}$, and in soil water 52 to $104 \mu\text{mol/l}$ (Van Stempvoort et al., 1992). It is not surprising then that precipitation and soil water can account for almost the entire sulfur budget (91%) of the Ottawa River basin (Table 5-1). The sulfur isotopes and sulfate concentrations of the tributaries can be used to explain the remaining 9%.

The SO_4^{2-} concentrations in the tributaries vary from ~60 to $500 \mu\text{mol/l}$, depending on the season and the geology of their basins (Figure 5-34). The South Nation River, which drains mid-Paleozoic carbonates and is heavily farmed, has very high concentrations of SO_4^{2-} (508 and $244 \mu\text{mol/l}$ for the spring and fall, respectively) and precipitation can account for only 35% of its sulfur budget. In contrast, relatively uninhabited tributaries draining the Precambrian silicate rocks, such as the Rivière Dumoine and Rivière Kipawa, have low SO_4^{2-} concentrations, 100% of which can be accounted for by inputs from precipitation. In fact, some of the dilute upland tributaries receive greater amounts of SO_4^{2-} from precipitation than can be accounted for by their concentrations. For example, precipitation inputs can account for 110% of the Rivière Dumoine (Table 5-1). These differences have been attributed to transport of sulfur in river organic matter (Beck et al., 1974), to biomass sulfur storage, and to the release of biogenic sulfur gases (Berner and Berner, 1996).

The non-precipitation flux of SO_4^{2-} in tributaries, such as the South Nation and Kenojevis Rivers, is derived from sources such as the dissolution of evaporite minerals, the

oxidation of sulfides, or from human sources, such as the smelting of sulfidic ores, chemical industry and petroleum refining. Since sulfur isotope fractionation between evaporitic sulfates and seawater is negligible (Nielsen, 1979), the $\delta^{34}\text{S}$ of dissolved SO_4^{2-} from evaporites in the Ottawa River basin should reflect that of mid-Paleozoic seawater SO_4^{2-} of about 20 to 30‰ (Claypool et al., 1980). As Figure 5-36 shows, some of the Paleozoic tributaries, particularly the Rigaud River, are shifted towards the $\delta^{34}\text{S}$ of marine sulfates, suggesting that the dissolution of gypsum or anhydrite is a contributor of SO_4^{2-} in these waters. This is a reasonable proposition since gypsum lenses have been reported in the March and Oxford sequences of the Ottawa Embayment (Hofmann, 1972). The lowest $\delta^{34}\text{S}$ values recorded in the waters of the Ottawa River basin, and some of the highest SO_4^{2-} concentrations, have been measured in the Kenojevis River which is the only major tributary partly draining an Archean Greenstone Belt. The Kenojevis basin also contains the large Rouyn-Noranda industrial complex, centred mainly on mining and smelting of sulfidic ore. The SO_4^{2-} concentrations and $\delta^{34}\text{S}$ values clearly reflect S input from oxidized pyrite. Unfortunately, because no other basins underlain by greenstone belts were studied for comparison, it is difficult to surmise whether the SO_4^{2-} is of natural or anthropogenic origins. The fact that this signal occurs only in the Kenojevis basin suggests that the source of the ^{34}S depleted SO_4^{2-} is localized. Bedrock distribution and/or direct industrial discharge are therefore more probable candidates for this source than is the atmospheric dispersal from smelter stacks.

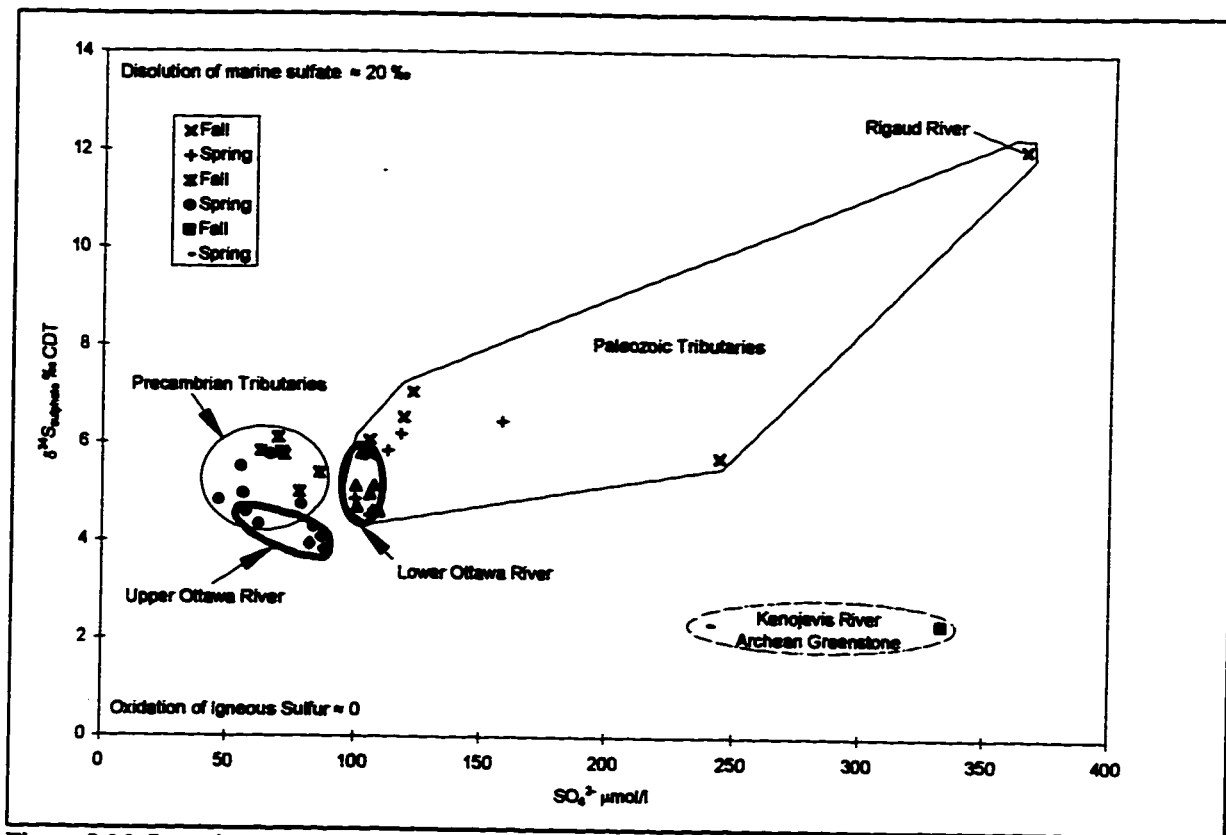


Figure 5-36: Isotopic composition of sulfate sulfur versus sulfate concentration for the Ottawa River and its tributaries.

Hitchon and Krouse (1972) and Reeder et al. (1972) studied sulfur in the Mackenzie River and concluded that the isotope composition of rock sulfur has a dominant effect on the $\delta^{34}\text{S}$ value of sulfate in rivers when anthropogenic pollution is not overwhelming. In the Ottawa River basin, the $\delta^{34}\text{S}$ value of sulfate in river water is dominantly controlled by the $\delta^{34}\text{S}$ composition of the rainfall, except in areas where the rock sulfur contributions (Paleozoic tributaries) or possibly industrial sulfur (Rivière Kenojevis) contributions are large enough to impact the precipitation flux. Ultimately, however, some 2/3 of the SO_4^{2-} in precipitation in the Ottawa River basin is believed to originate from anthropogenic sources such as fossil fuel burning and smelting of sulfidic ore (Berner and Berner, 1996). This implies that the dominant control of the sulfur cycle in the Ottawa River basin is anthropogenic.

5.6 STRONTIUM

The temporal and spatial distribution pattern of Sr^{2+} in the Ottawa River basin, mirrors that of the major ions, such as Ca^{2+} , Mg^{2+} and DIC. Typical values for the Ottawa River are in the 0.15 to 0.68 $\mu\text{mol/l}$ range while for the tributaries they are from 0.14 to 14.68 $\mu\text{mol/l}$. Concentrations in the spring are frequently lower than in the fall in the upland basins due to dilution and higher in the lowland basins due to hysteresis (Figure 5-37). Concentrations of Sr^{2+} in the Ottawa River are diluted in the springtime.

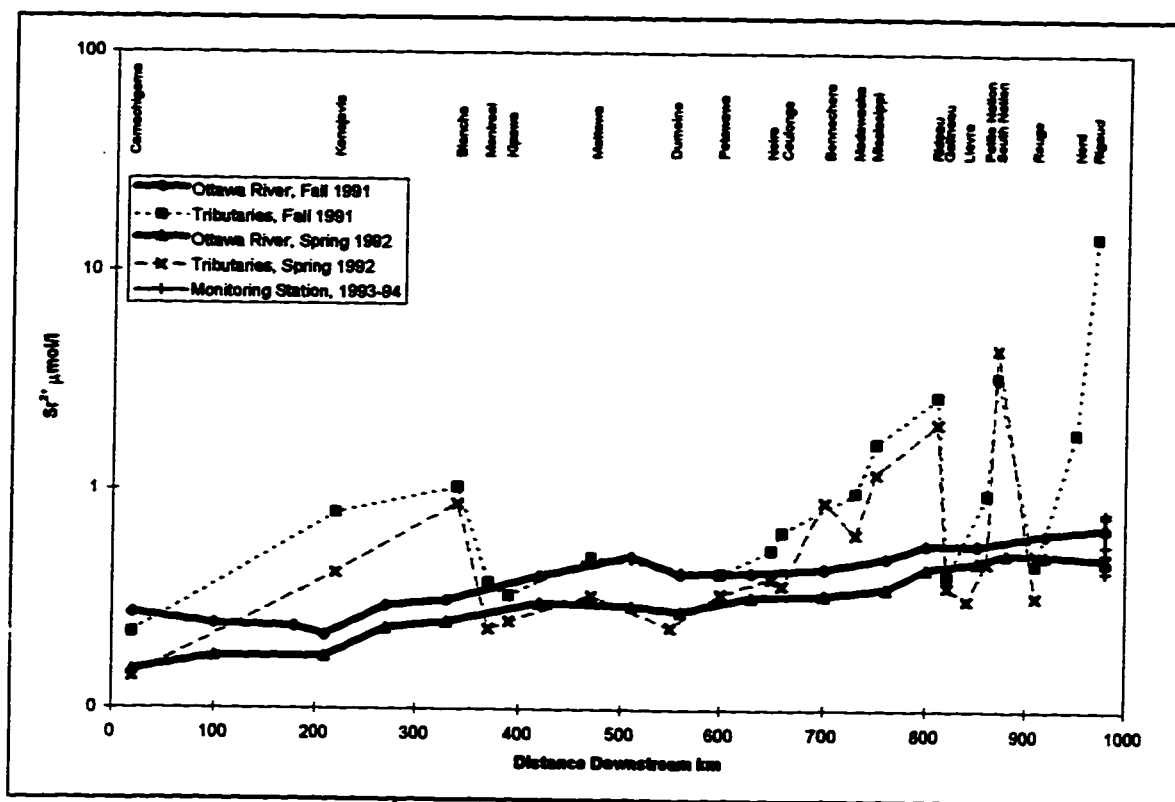


Figure 5-37: The distribution of Sr^{2+} in the Ottawa River and its tributaries in the fall and the spring.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the Ottawa River and its tributaries (Figure 5-38) is a product of hydrology and geology. The distinct sources of Sr^{2+} are clearly differentiated in Figure 5-39. The pattern is reminiscent of the one previously published by Wadleigh et al. (1985) for Canadian rivers and by Palmer and Edmond (1992) for world rivers. Rivers draining old,

silicate dominated, shield terrains have Sr^{2+} concentrations $\leq 0.5 \mu\text{mol/l}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in excess of 0.712. The lowland Paleozoic tributaries, such as the South Nation and Rideau Rivers, draining the Ordovician carbonates, define the opposite end-member with Sr concentrations of $1\text{--}10 \mu\text{mol/l}$ and non-radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of less than 0.711, comparable to that of mid-Paleozoic sea water (Burke et al., 1982). Tributaries draining a mix of Precambrian and Paleozoic geology and the lower Ottawa River, which integrates the signal from Precambrian and Paleozoic terrains, plot in-between the two endmembers. The headwaters are somewhat mysterious as they are less radiogenic than would be expected for waters draining the Precambrian gneisses. Much of the headwater terrains have been metamorphosed during the Grenville Orogeny and so it is possible that $^{87}\text{Sr}/^{86}\text{Sr}$ contamination or Rb depletion occurred.

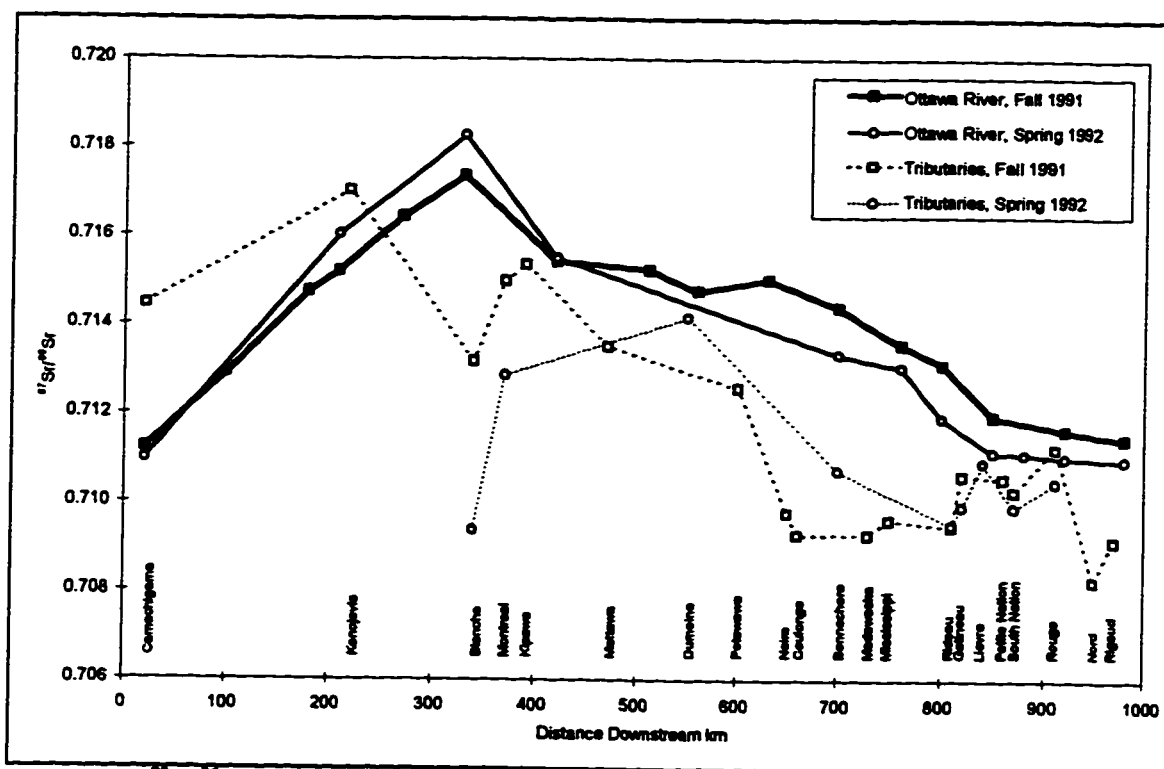


Figure 5-38: $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of waters in the Ottawa River basin.

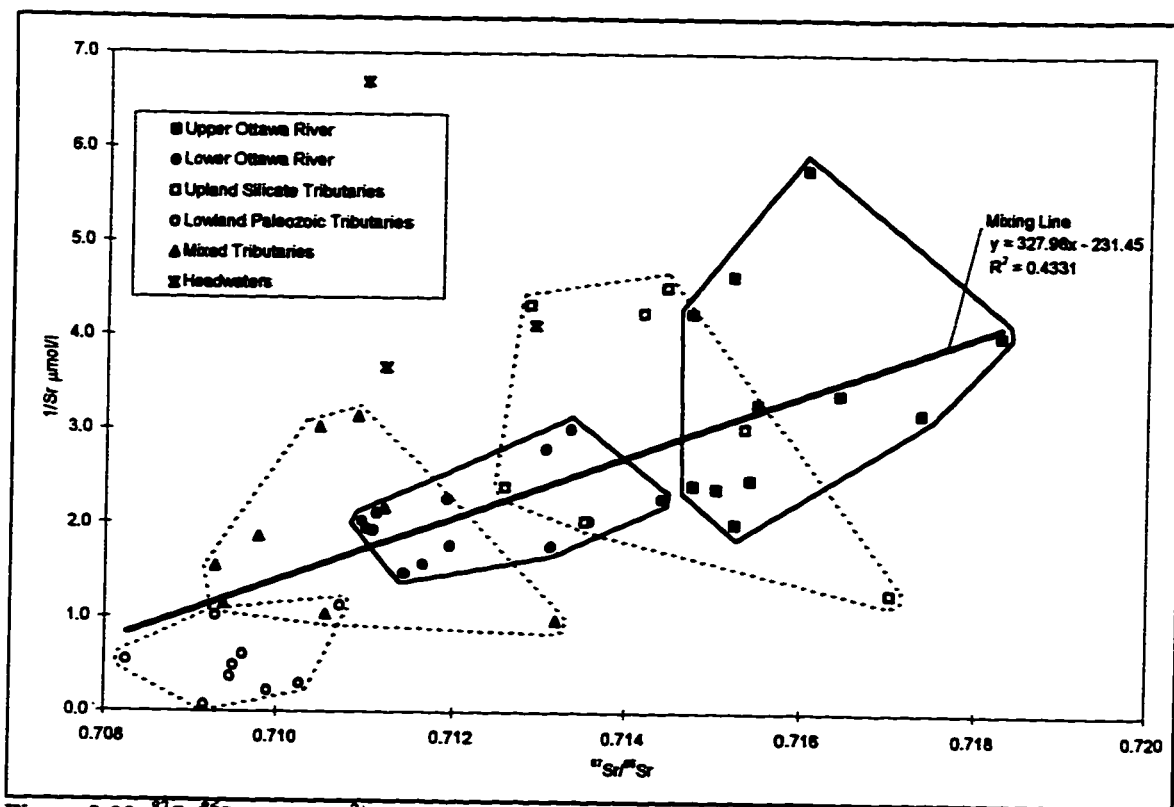


Figure 5-39: $^{87}\text{Sr}/^{86}\text{Sr}$ versus Sr^{2+} for waters in the Ottawa River basin.

The mean annual flux of Sr at the mouth of the Ottawa River is 1.08 mol/s or 3.4×10^7 mol/a (Figure 5-40), representing roughly 0.16% of the global riverine flux of Sr^{2+} to the oceans (Wadleigh et al., 1985; Palmer and Edmond, 1992). The biggest source of Sr^{2+} to the Ottawa River is the South Nation River in the springtime, although it is superseded by the Rivière Gatineau in the fall, similar to the pattern for other major ions. Sr^{2+} behaves in a conservative manner in the Ottawa River, as evident by the absence of any negative slopes on the flux curves of the Ottawa River in Figure 5-40.

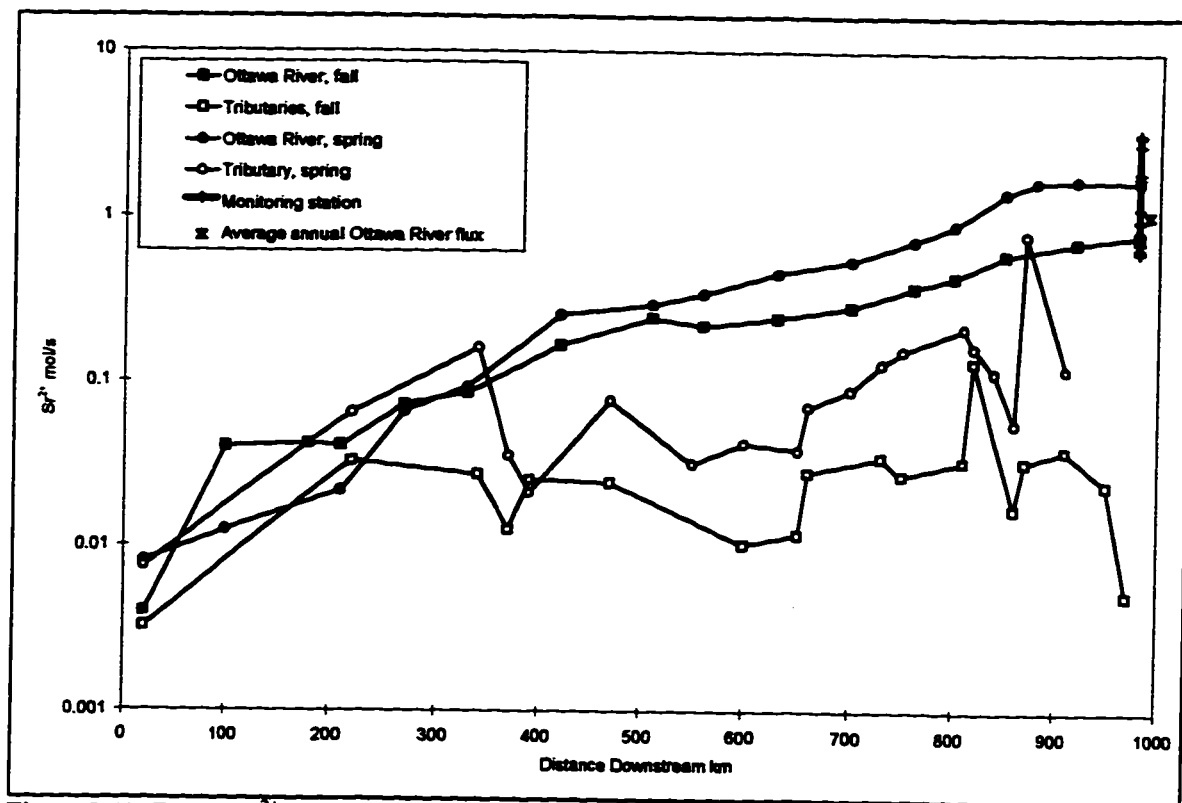


Figure 5-40: Flux of Sr^{2+} from the Ottawa River and its tributaries for the spring and fall.

5.7 DOMINANT CONTROLS ON RIVER CHEMISTRY

The innumerable possibilities for analyses with a dataset as large as the one produced by this research (see chapter 3 for details) make it impossible to analyze it in detail within the constraints of a thesis. For example, the behavior of trace elements in the Ottawa River basin has not yet been addressed. Multivariate statistical techniques provide a means of disseminating gross trends from large datasets, thus utilizing all of the data to some degree. This is the approach used below.

5.7.1 Principal Components Analysis

Principal component analysis (henceforth PCA) was done in SYSTAT (SYSTAT Inc., 1993). Since the variables are in different units, and their relative variability can be very

different, the data were first standardized by subtracting the mean and dividing by the standard deviation. The PCA was performed on a correlation matrix. The details of PCA are described in Davis (1986).

PCA based on chemical variables of the tributaries, identified 3 components controlling the overall chemistry of waters in the Ottawa River basin. These 3 components explain 88 and 81% of the total variance in the spring and fall, respectively (Table 5-4). Additional components explain little of the variance per component, each represented by only 1-2 variables, thus yielding little further insight into the controls on river chemistry.

a.				
Spring Parameters	Varimax Rotated Component Loadings			
	1	2	3	
Mg	0.97			
Sr	0.97			
Conductivity	0.97			
K	0.96			
Cl	0.95			
SO ₄	0.95			
Ca	0.95			
Na	0.94			
HCO ₃	0.91			
pH	0.67	0.59		
δ ³⁴ S	-0.52	0.68		
Si	-0.74	-0.45		
δ ¹³ C		0.80		
δ ¹⁸ O		0.63		
⁸⁷ Sr/ ⁸⁶ Sr		-0.75		
Fe			-0.91	
Mn			-0.93	
Percent of total variance explained	57.4	17.6	13.9	total 88.9

b.				
Fall Parameters	Varimax Rotated Component Loadings			
	1	2	3	
Cl	0.96			
Na	0.95			
Conductivity	0.94			
Sr	0.92			
Mg	0.88			
Ca	0.85	0.40		
HCO ₃	0.85	0.41		
K	0.80			
SO ₄	0.68			
pH	0.63	0.47		
δ ¹³ C		0.84		
δ ¹⁸ O		0.61		
⁸⁷ Sr/ ⁸⁶ Sr		-0.60		
Si		-0.73		
δ ³⁴ S			0.92	
Fe			-0.69	
Mn			-0.94	
Percent of total variance explained	44.1	18.0	19.0	total 81.1

Table 5-4: Principal component loadings for chemical parameters of the tributaries of the Ottawa River, in descending order. a. Spring 1992; b. Fall 1991.

The major ions, conductivity, and pH, load on the dominant component 1 and thus it represents the geogenic process of chemical weathering (dominantly carbonate weathering) and to a lesser degree, anthropogenic pollution from road salting, industry and agriculture. Component 2, containing primarily parameters which have distinctively different signals for upland shield waters than for lowland carbonate waters (isotopes, pH, and silica), represents

the shift from the shield to the lowlands. Component 3 is typified by decreasing Fe and Mn concentrations. These concentration of these elements is often controlled by the distribution of fine particulates such as colloids and, therefore, component 3 likely represents changes in the nature of the suspended load. The physico-chemical changes occurring with a shift from high latitude, high altitude, pristine, silicate shield catchments to low latitude, low altitude, industrialized, carbonate catchments can account for all three components, a downstream trend.

Seasonally, the percentage of the total variance for each component shifts moderately. For example, component 1 accounts for 57 and 44% of the total variance in the spring and fall, respectively. Differences in the seasonal behavior of the lowland tributaries versus the upland tributaries can explain the shift in component 1. In the spring, concentrations in the lowland and upland tributaries move in opposite directions, with the lowlands becoming more concentrated, therefore increasing the variance of the major ions, which, in turn, causes component 1 to become more dominant. Isotope ratios are relatively unaffected by shifts in discharge and concentration and, therefore, the variance explained by component 2, dominantly represented by isotopes, is relatively constant seasonally. The greater relative strength of component 3 in the fall is, at least partially if not mainly, an artifact of the reduced relative importance of component 1.

In order to explore further the origins of river chemistry and to corroborate the above results, another PCA based on all spatial, chemical, hydrological, and physical variables of the tributaries was carried out. This identified 2 major and 3 minor components. Figure 5-41 shows the percentage of variance explained versus the number of components chosen for the

spring. The pattern for the fall is similar. 5 components explain roughly 75% of the variance.

Additional components explain less than 6% of the variance per component, each represented by only 1-3 variables.

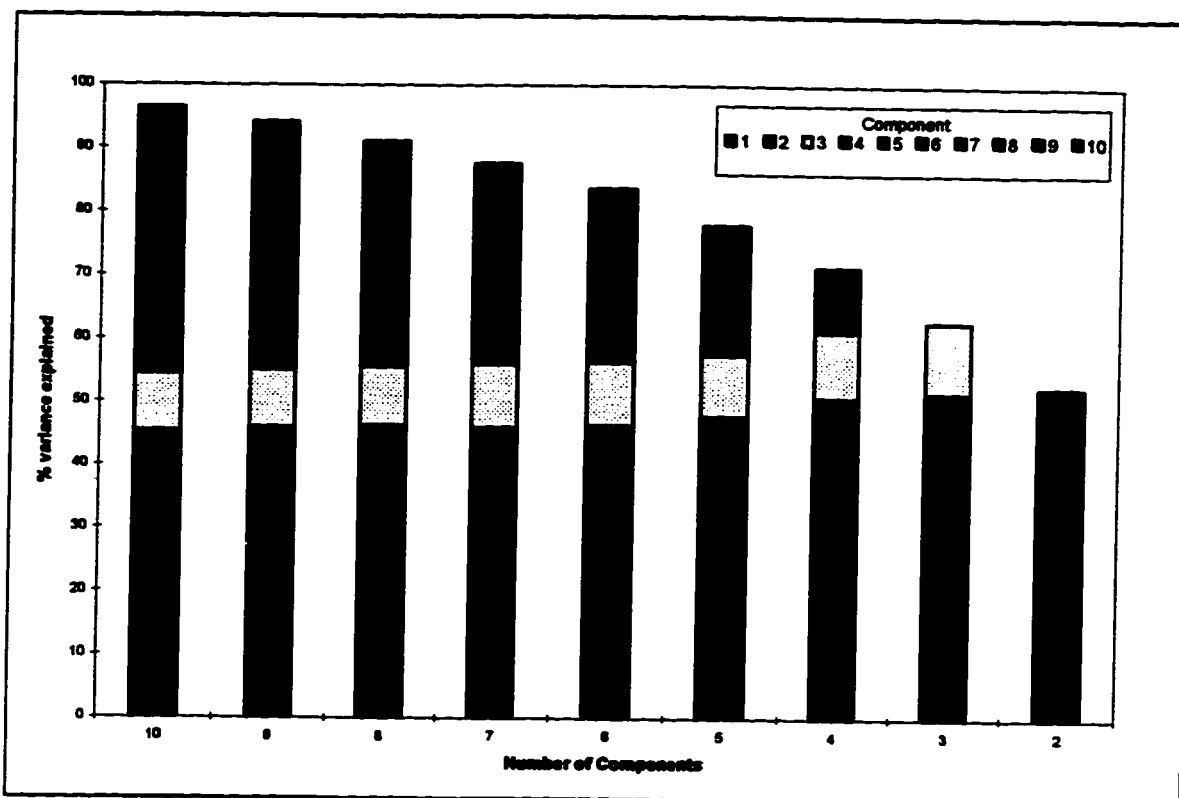


Figure 5-41: Percent variance explained versus the number of components chosen in PCA of spring data, varimax rotated.

The varimax rotated component loadings for 5 components for the spring and fall are listed in Tables 5-5 and 5-6. The dominant component 1 represents ~30% of the variance, slightly higher in the spring and lower in the fall, and bears the signal of the lowlands. Parameters that have positive loadings, such as the percentage of carbonate bedrock, Ca^{2+} , and Cl^- concentrations, agricultural landuse and CV are characteristic of the lowlands, whereas parameters with negative loadings, such as altitude, Si and the percentage of deciduous forest, are uncharacteristic. Component 1, therefore, represents predominantly the geogene process of carbonate weathering and subdominantly anthropogenic pollution from

road salting, industry and agriculture in agreement with the PCA based only on chemical variables (Table 5-4). Due to the nature of the geography in the Ottawa River basin, the carbonate lowlands are also the sites of intense agricultural and industrial activity and high population density. As a result, loadings from anthropogenic inputs coincide with those from carbonate dissolution.

Component 2, which is typified by decreasing latitude, decreases in trace elements such as Fe, Mn, and Ti (Ti was measured in the spring only), and by enrichments of ^{13}C , ^{18}O and ^{34}S , represents a shift from the upland silicate shield and greenstone volcanic belt to the Paleozoic lowlands and the associated changes in the suspended load - a latitudinal trend. This component accounts for ~15% of the total variance. Note that this component is a combination of components 2 and 3 from the PCA based only on chemical variables (Table 5-4).

The third component, which accounts for 13% and 11% of total variance in the spring and fall, respectively, represents the shift from highly resistant plutonic gneisses to less resistant metamorphic assemblages, changes in a longitudinal direction. For example, the percentage of metasedimentary bedrock and the amount of precipitation is relatively greater in the east than the west, vice versa for plutonic bedrock. The chemical changes associated with a longitudinal trend are less pronounced than those associated with a latitudinal trend because the changes in lithology and physiography are more subtle. For example, in the fall, K^+ and Zn appear to be higher in eastern parts of the basin. Note, however, that K^+ loads also on component 1, particularly in the spring when flux from the lowland tributaries is high.

Parameters that load on component 4 are exclusively hydrological variables, such as precipitation, reservoir capacity, and auto and cross correlation coefficients of discharge. Thus component 4, which can account for ~10% of the total variance, represents the water balance of the basin including its anthropogenic manipulation. Interestingly, there is not a strong chemical signal associated with this component.

Component 5 represents soil productivity. As the percentage of organic carbon in soils decreases, $\delta^{13}\text{C}_{\text{DIC}}$ increases as does the pH, as would be expected for low productivity soils with low CO_2 production. The same chemical signature could be explained by increased abundance of carbonate in soils but this can be ruled out since parameters related to carbonate distribution do not load on this component.

Spring Parameters	Varimax Rotated Component Loadings				
	1	2	3	4	5
Mg	0.97	-	-	-	-
Conductivity	0.97	-	-	-	-
V	0.97	-	-	-	-
Cl	0.97	-	-	-	-
Sr	0.96	-	-	-	-
Na	0.96	-	-	-	-
K	0.96	-	-	-	-
Clastic Bedrock %	0.95	-	-	-	-
Ca	0.95	-	-	-	-
Agricultural Land Use %	0.94	-	-	-	-
Carbonate Bedrock %	0.94	-	-	-	-
SO ₄	0.93	-	-	-	-
HCO ₃	0.93	-	-	-	-
Coefficient of Variance (CV) for discharge	0.87	-	-	-	-
Ba	0.86	-	-	-	-
Rural Population	0.82	-	-	-	-
Calcite Saturation Index	0.69	-	-	-	0.51
pH	0.63	-	-	-	0.59
Coniferous forest, % of existing forest	0.53	-	-	-	0.58
Urban Population	0.53	-	0.57	-	-
NO ₃	0.51	-	-	-	-
Deciduous Forest, % of existing forest	-0.53	-	-	-	-0.58
Dissolved Oxygen	-0.64	-	-	-	-
Mixed wood Forest, % coverage	-0.64	-	-0.63	-	-
Si	-0.76	-	-	-	-
Basinal Altitude	-0.85	-	-	-	-
δD	-	0.65	-	-	-
$\delta^{34}S$	-	0.62	-	-	-
$\delta^{18}O$	-	0.61	-	-	-
Precipitation, average April	-	0.52	-	0.52	-
Water Temperature	-	0.51	-	-	-
Mn	-	-0.62	-	-	-
Co	-	-0.62	-	-	-
Coniferous forest, % coverage	-	-0.63	-	-	-
Zn	-	-0.65	-	-	-
Ni	-	-0.66	-	-	-
Fe	-	-0.67	-	-	-
Volcanic Bedrock %	-	-0.72	-	-	-
Average basinal latitude	-	-0.76	-	-	-
Cu	-	-0.78	-	-	-
Al	-	-0.86	-	-	-
Ti	-	-0.93	-	-	-
Lag at Maximum Cross Correlation Coefficient	-	-	0.82	-	-
Metasedimentary Bedrock %	-	-	0.70	-	-
Deciduous Forest, % coverage	-	-	0.67	-	-
Average basinal Longitude	-	-	0.66	-	-0.54
Reservoir Capacity	-	-	0.61	-0.91	-
Charge Balance	-	-	-0.52	-	-
Plutonic Bedrock %	-	-	-0.77	-	-
$^{87}Sr/^{86}Sr$	-	-	-0.78	-	-
Cross Correlation Coefficient - Maximum	-	-	-	1.00	-
Autocorrelation Coefficient at Lag = 1 year	-	-	-	0.91	-
Annual Precipitation	-	-	-	0.68	-
Generating Capacity	-	-	-	-0.78	-
Basinal Area	-	-	-	-0.83	-
Average depth to water table	-	-	-	-	0.83
$\delta^{13}C$	-	-	-	-	0.51
Lag for Autocorrelation to drop below 0.8	-	-	-	-	-0.55
Organic Carbon, % in Soil	-	-	-	-	-0.75
Nitrogen, % in soil	-	-	-	-	-0.80
Percent of total variance explained	32.3	15.4	10.4	10.0	9.7

Table 5-5: Principal component loadings for all parameters of tributaries of the Ottawa River, spring 1992, in descending order.

Fall Parameters	Varimax Rotated Component Loadings				
	1	2	3	4	5
Conductivity	0.96	-	-	-	-
Mg	0.96	-	-	-	-
Sr	0.95	-	-	-	-
Carbonate Bedrock %	0.95	-	-	-	-
Agricultural Land Use %	0.94	-	-	-	-
Cl	0.92	-	-	-	-
V	0.92	-	-	-	-
Na	0.89	-	-	-	-
HCO ₃	0.89	-	-	-	-
Clastic Bedrock %	0.89	-	-	-	-
Ca	0.88	-	-	-	-
Coefficient of Variance (CV) for discharge	0.86	-	-	-	-
Calcite Saturation Index	0.74	-	-	-	-
Coniferous forest, % of existing forest	0.66	-	-	-	-
SO ₄	0.65	-	-	-	-
pH	0.59	0.50	-	-	-
Evapotranspiration, annual	0.58	-	-	-	-
K	0.57	-	0.63	-	-
Urban area %	0.52	-	-	-	-
$\delta^{18}\text{O}$	0.51	-	-	-	-
Plutonic Bedrock %	-0.55	-	-0.64	-	-
Mixed wood Forest, % coverage	-0.62	-	-0.70	-	-
Deciduous Forest, % of existing forest	-0.66	-	-	-	-
Basinal Altitude	-0.69	-	-	-	-
$\delta^{34}\text{S}$	-	0.84	-	-	-
Air Temperature, average October	-	0.82	-	-	-
$\delta^{13}\text{C}$	-	0.61	-	-	-
Dissolved Oxygen	-	0.53	-	-	-
Volcanic Bedrock %	-	-0.61	-	-	-
Mn	-	-0.63	-	-	-
NO ₃	-	-0.67	-	-	-
Fe	-	-0.68	-	-	-
Si	-	-0.70	-	-	-
Al	-	-0.72	-	-	-
Coniferous forest, % coverage	-	-0.81	-	-	-
Average basinal latitude	-	-0.84	-	-	-
$^{87}\text{Sr}/^{86}\text{Sr}$	-	-0.86	-	-	-
Lag at Maximum Cross Correlation Coefficient	-	-	0.86	-	-
Deciduous Forest, % coverage	-	-	0.76	-	-
Phosphate	-	-	0.76	-	-
Average basinal Longitude	-	-	0.68	-	-
Metasedimentary Bedrock %	-	-	0.67	-	-
Water Temperature	-	-	0.65	-	-
Annual Precipitation	-	-	0.64	0.59	-
Precipitation, Average November	-	-	0.56	-	-
Zn	-	-	0.53	-	-
Evapotransp Fall	-	-	0.52	-	-
Cross Correlation Coefficient - Maximum	-	-	-	0.99	-
Autocorrelation Coefficient at Lag = 1 year	-	-	-	0.93	-
Open Water %	-	-	-	-0.52	-
Generating Capacity	-	-	-	-0.67	-
Basinal Area	-	-	-	-0.85	-
Reservoir Capacity	-	-	-	-1.07	-
Nitrogen % in soil	-	-	-	-	0.80
Organic Carbon % in Soil	-	-	-	-	0.77
First Order Autocorrelation Coefficient	-	-	-	-	0.54
Average depth to water table	-	-	-	-	-0.84
Percent of total variance explained	28.8	15.8	13.2	10.9	8.2

Table 5-6: Principal component loadings for all parameters of tributaries of the Ottawa River, fall 1991, in descending order.

5.7.2 Chemical Classification

Several classification schemes based on major ion geochemistry have been devised for characterizing surface waters and discerning their origin. Gibbs (1970) used TDS versus $\text{Na}/(\text{Na}+\text{Ca})$ ratios to classify surface waters resulting in three genetic endmembers:

1. **Precipitation dominance.** The compositions of these waters resemble rainfall, they are dilute and with high Na^+ relative to Ca^{2+} . Examples are the floodplain tributaries of the Amazon River.
2. **Rock dominance.** Most of the world's rivers plot in this category categorized by intermediate TDS and by much greater concentrations of Ca^{2+} due to the weathering of minerals (dominantly CaCO_3).
3. **Evaporation dominance.** Rivers in this category supposedly drain arid regions where evaporation is high, increasing TDS and causing calcite to precipitate, enriching the residue in Na^+ relative to Ca^{2+} .

However, this widely accepted classification scheme has proved to be generally wrong.

Stallard and Edmond (1983) show that geology and erosional regime can explain the characteristics of all waters used in Gibbs' classification and in particular that the dilute waters of the Amazon floodplain do not have a chemistry that is controlled by meteoric precipitation. Drever (1988) also emphasizes the role of geology as a control on river composition. Others have shown that waters plotting close to the "evaporation" endmember are the result of evaporite weathering and not of evaporation with subsequent calcite precipitation (Berner and Berner, 1996; Stallard, 1980). In fact some rivers draining arid regions such as the Indus River

in Pakistan undergo less evapotranspiration than those in humid regions due to the dearth of vegetation (Karim, pers. comm., 1996).

Berner and Berner (1996) found Stallard's and Edmond's (1983) classification for Amazon basin rivers, based on total cationic charge, to be useful also for rivers outside the tropics. It also nicely classifies the Ottawa River and its tributaries into 4 genetic categories (Table 5-7). The first category ($<200 \mu\text{eq/l}$) describes rivers draining intensely weathered, cation poor siliceous rocks, soils, and saprolites and supplants Gibbs' "precipitation dominated" endmember. Waters draining these environments should have $\text{Si}/(\text{Na}+\text{K})$ ratios roughly equal to 2, in accordance with the stoichiometry of feldspar weathering to kaolinite. The highly weathered environment ascribed to the classification scheme by Stallard and Edmond does not exist in the Ottawa River basin but nonetheless some of the dilute upland waters fit well in this category, illustrating that, for different reasons than those in the tropics, such as the absence of soil and vegetation development, very low weathering rates occur in the uplands.

The second category ($200\text{--}450 \mu\text{eq/l}$) represents waters draining silicate terrains devoid of carbonates. The upland tributaries and upper reaches of the Ottawa River drain such environments and thus they plot in this category. The water chemistry ascribed to this category by Stallard and Edmond is similar to that of the first group, with $\text{Si}/(\text{Na}+\text{K})=2$, after corrections for cyclic salt. Ottawa River basin waters that plot in category 2 have $\text{Si}/(\text{Na}+\text{K})$ values lower than 2 and often close to 1. Several reasons can account for this. (1) Na^+ has not been corrected for cyclic salt inputs. The presence of non-silicate based Na^+ could produce the observed $\text{Si}/(\text{Na}+\text{K})$ values. Cyclic salt corrections were tried but produced unsatisfactory

results, probably due to the different behaviour of Na^+ versus Cl^- outlined in section 5.2 or due to pollution sources (e.g. water treatment operations) which contribute only Cl^- . The Na/Cl ratio is included in category 2 of Table 5-7 to show that Cl^- exists sometimes in excess of Na^+ .

(2) Due to its stoichiometry, the weathering of anorthite or strongly calcic plagioclase to kaolinite does not release H_4SiO_4 into solution producing $\text{Si}/(\text{Na}+\text{K})$ values lower than 2. Anorthosites occur in the uplands.

The third category (450-3000 $\mu\text{eq/l}$) represents rivers draining calcareous rocks, such as limestones, dolomites and calcareous shales. These rivers are characterized by 1:1 ratios for $\text{Na}:\text{Cl}$ and $(\text{Ca}+\text{Mg}):(\frac{1}{2}\text{HCO}_3^- + \text{SO}_4^{2-})$, the ratios expected for the weathering of carbonate and evaporite lithologies. These expectations are met by roughly one half of waters from the Ottawa River basin. This category includes most major world rivers and corresponds to Gibbs' Rock dominance category.

The fourth category, which comprises rivers draining evaporites, is represented in the Ottawa River basin by the high TDS lowland tributaries. The characteristic water chemistry is similar to that of category 3, the main distinction being the increased TDS due to greater amounts of evaporite weathering. As discussed earlier in this chapter, the major source of the "evaporite" salts in the lowland tributaries is most likely natural, but not due to the genetic reasons proposed by Stallard and Edmond. Fine grained fresh materials produced by recent glaciation (rock flour of the Leda Clay) are easily weathered, thus emulating the high weathering rates and high TDS waters. The same is true of salt leaching from sediments deposited during recent marine incursions. Thus geological history also plays a major role in controlling the chemistry of rivers.

Total Cationic Charge ($\mu\text{eq/l}$)	<200			200-450			450-3000			>3000		
	pH	Na/Cl	Si/ (Na+K)	pH	Na/Cl	Si/ (Na+K)	pH	Na/Cl	(Ca+Mg)/ ($\frac{1}{2}\text{HCO}_3$ + SO_4)	pH	Na/Cl	(Ca+Mg)/ ($\frac{1}{2}\text{HCO}_3$ + SO_4)
Ottawa River												
Headwaters	6.2	0.54	1.97									
Lac Dozois	6.6	0.78	1.45									
Lac Granet				7.1	1.33	0.92						
Rapide Sept				6.9	1.01	1.02						
Lac Simard				7.1	1.42	0.87						
Notre Dame du Nord				7.2	1.23	0.83						
Terniskaming							7.6	1.00	1.12			
Duex Rivière							7.3	0.86	0.75			
Rolphton							7.3	1.38	1.06			
Pembroke							7.6	1.43	1.00			
Portage du Fort							7.9	1.15	1.01			
Quyon							7.7	1.50	1.00			
Champlain Bridge							7.9	0.93	0.94			
Cumberland							7.7	1.94	1.04			
Hawkesbury							7.5	0.91	1.05			
Carleton							7.0	1.17	1.06			
Tributaries												
Camachigama	6.4	0.56	1.93									
Kenojevis							7.6	0.97	1.03			
Blanche							7.2	1.04	1.15			
Montreal							8.0	1.04	1.13			
Kipawa				6.7	0.79	1.14						
Mattawa				7.2	0.90	0.54						
Dumoine				6.4	0.96	1.41						
Petawawa				7.0	0.48	1.09						
Noire				6.9	1.13	1.33						
Coulange				6.9	0.95	1.13						
Bonnechere							8.0	0.45	1.00			
Madawaska							8.7	1.03	1.09			
Mississippi							8.7	0.95	1.08			
Rideau										8.2	0.51	1.14
Gatineau				7.0	1.72	0.76						
Rivière du Lièvre							7.3	0.49	1.27			
Petite Nation							8.1	0.98	1.07			
South Nation										8.4	0.41	1.12
Rouge				8.1	0.51	0.76						
Nord										8.3	1.02	1.07
Rigaud										8.5	1.00	1.08

Table 5-7: Waters of the Ottawa River basin classified according to Stallard and Edmond's (1983) river classification. Ottawa River locations and tributaries are arranged from top to bottom in downstream order.

6 CONCLUSIONS

The Ottawa River basin, at 149,000 km², is the largest river basin in eastern Canada. It has a mean annual discharge of 1934 m³/s, mean annual precipitation of 872mm and a mean annual temperature of 3.5 °C. The basin is underlain by 60% Precambrian plutonic rocks, 28% metamorphic rocks of Grenville age, 6% Paleozoic carbonate rocks, 4% Archean volcanics, and 2% Paleozoic clastic rocks. The Paleozoic sediments reside mainly in the south of the basin and are extensively covered by Quaternary tills and glaciomarine sediments which have developed thick productive soils since the retreat of the Wisconsinan ice sheet. The physically resistant Canadian Shield, which predominates in the north of the basin, contains only thin and discontinuous tills and sediments and consequently soils are sparse and poorly developed. The chemistry of the waters which drain this varied terrain are the result of the interaction of the geology and its related characteristics with the hydrologic cycle, with the latter being strongly influenced by the former.

The hydrological cycle results from the interaction of seasonal and spatial climate changes and physical basin characteristics such as soil type, water storage capacity, vegetation cover, and biomass (all of which are ultimately controlled by geology) as well as hydroelectric operations and possibly landuse. Hydrology alters river chemistry primarily by varying the fluxes of water from different sources through time and secondly by dilution and possibly hysteresis. The chemistry of basinal waters is controlled primarily by the weathering of different lithologies and their related soils and biomass and secondly by anthropogenic inputs such as road salt, fertilizer, municipal and industrial discharge. The interaction of the hydrologic cycle with the chemical controls produces a relatively consistent seasonal

biogeochemical cycle which is primarily of natural origin but has been altered significantly by humans. Figure 6-1 summarizes this cycle.

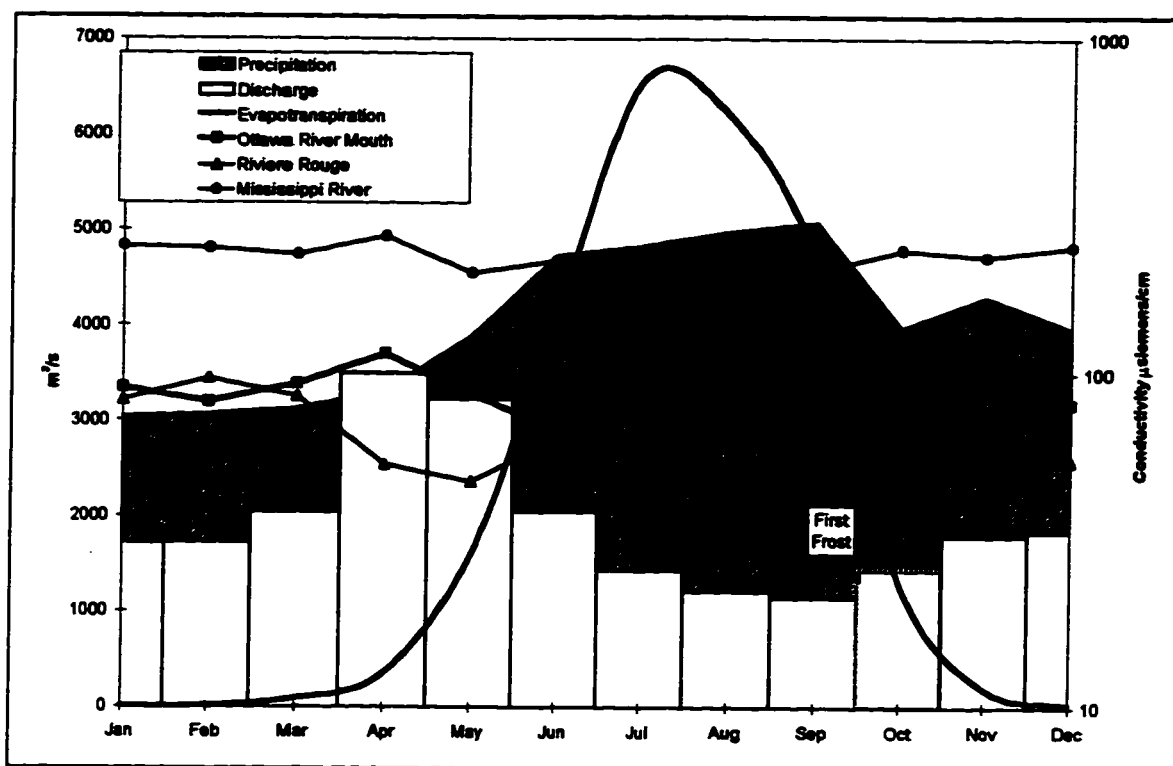


Figure 6-1: Mean water balance and conductivity for the Ottawa River basin. Conductivity data for the Mississippi River and Rivière Rouge is from Environment Canada, 1991.

6.1 HYDROLOGY

51% of annual precipitation is returned to the atmosphere by evapotranspiration, mainly during the growing season when basinal temperature is high. Of this, 43% is transpired and intercepted and 8% is evaporated. Groundwater recharge does not occur during the growing season because the precipitation flux (62 km^3) and evapotranspiration flux (63 km^3) during this period (summer/fall) are essentially balanced. This implies that baseflow is maintained exclusively by non-growing-season precipitation (late fall, winter, and earliest spring). This is more or less true for different parts of the basin with cooler upland regions

releasing their water more slowly and evapotranspiring less (40%) than the warmer lowlands (65%).

Discharge peaks in the spring due to snow melt and in the late fall when frost terminates transpiration, directly out of phase with precipitation inputs. The upland tributaries flood more slowly and between 20 and 30 days after the lowland tributaries. They contribute a relatively greater proportion of water to the Ottawa River during low water stand than the lowland tributaries which are characterized by short-lived high-discharge pulses in the spring and late fall and very low discharge in the summer and winter. These characteristics are primarily due to climatic and physiographic conditions, such as the cooler temperatures and greater water-storage capacity of the upland tributary basins and the tarmac-like low permeability clays of the lowlands, but have been accentuated by the flow augmentation practices of reservoir operators.

6.2 CHEMISTRY

Fluctuations in the chemical composition of waters at the mouth of the Ottawa River are controlled by the hydrological phenomena. Contributions of TDS from the lowland tributaries are relatively greater than those of the upland tributaries in the spring and late fall, but they are superseded in importance by the upland tributaries in the summer and winter. Mixing of the highly variable lowland inputs with the more stable flows from the uplands causes the TDS and all major ions (proportional to the conductivity shown in Figure 6-1) of the Ottawa River to peak in April along with the discharge of the lowland tributaries and to bottom out in the summer when discharge from the dilute uplands is relatively more important, a pattern which could be erroneously ascribed to the process of hysteresis. In this

way, the chemistry of the Ottawa River deviates towards that characteristic of a carbonate drainage basin in the spring and the late fall, and toward that of a silicate drainage basin in the summer and winter, although, overall, it is dominated by the volumetrically more important silicate catchments. The fluctuations are moderately dampened by hydroelectric practices.

The relationship of discharge to the dissolved load of waters in the Ottawa River varies in space depending on the nature of the substrate, with seasonal dilution predominant in the silicate uplands and weak hysteresis in the carbonate lowlands. The TDS of the Mississippi River and Rivière Rouge illustrate this in Figure 6-1. The causes of these spatial differences are both hydrological and geological. Discharge in the lowlands is more variable, with extremely low discharge in the summer (below detection of the gauge at the South Nation River), allowing concentrated residues to build up before being washed out during high flow periods. This is complemented by the presence of geologic materials, such as carbonates, which are more easily dissolved. The more stable discharge of the uplands drains chemically resistant material preventing the accumulation of concentrated residues. Alternatively, the hysteresis signal evident in the lowlands could be explained by shifting seasonal sources, as is the case for the Ottawa River.

Spatially, the chemistry of waters in the Ottawa River basin is controlled by the rates and products of rock weathering, which in turn are controlled by the susceptibility of different minerals to weathering as well as by soil respiration rates, the latter controlling the amount of carbonic acid available for weathering. Chemical signals caused by respiration and photosynthesis within the river itself are not evident or are secondary.

The generation of carbonic acid by organic respiration in the soil zone is much higher in the well developed soils of the lowlands than in the sparse soils of the uplands. A hypothetical soil $p\text{CO}_2$ for upland silicate, mixed, and lowland carbonate basins is calculated to be roughly 2000, 5000, and 30,000 ppm, respectively, although locally higher values can be expected. Waters draining these soils react with minerals in the soils and bedrock until either calcite saturation is reached, as is the case for the lowland carbonate tributaries, or until they discharge from the water/rock interface as is the case for the silicate basins. In mixed basins, both processes occur and the resulting waters represent a mix of the two end-members. This is the case for the Ottawa River.

For an entirely carbonate basin, the relative contribution to the DIC budget from organic respiration and carbonate dissolution would be 50% from each source. The Ottawa River basin is underlain by only ~8% calcareous rocks yet, ^{13}C mass balance calculations show that 61% of the DIC in the Ottawa River originates from organic respiration and 39% from carbonate dissolution. This illustrates the resistant nature of silicate rocks and the dominant role of carbonates on controlling chemistry of surface waters. From this calculation and from the stoichiometry of carbonate dissolution, it follows that 75% of the total $[\text{Ca}^{2+} + \text{Mg}^{2+}]$ originates from carbonate weathering and 25% from silicate weathering plus atmospheric and other inputs.

Carbon isotopes suggest that CO_2 exchange with the atmosphere is unidirectional (evasion to the atmosphere) or volumetrically unimportant. The Ottawa River discharges $4.3 \times 10^{10} \text{ molC/a}$ as DIC, representing 0.13% of the global DIC riverine flux and 11% of the flux from the St. Lawrence River. Carbon isotopes indicate that 61% of this is derived from

respiration and, assuming a respiration rate of $5\text{mmolC/m}^2/\text{hr}$ for the basin, the Ottawa River would transport about 6.6% of the respired carbon from the basin. The remainder evades directly to the atmosphere from soils. Calculations based on a diffusion model produce a first order estimate of CO_2 evasion to the atmosphere. For the Ottawa River and its tributaries it is $\sim 1.3 \times 10^{10} \text{molC/a}$ or roughly 30% of the DIC flux.

Cl^- and Na^+ in the Ottawa River are derived primarily from sea salt that is either trapped in pore waters of sediments or present as sedimentary halite. The secondary source is atmospheric cyclic salt input (17%) and third source may be road salting and municipal and industrial discharge. The importance of these sources varies tremendously in the basin, with the more dilute headwaters being dominated by atmospheric input and the lowlands by sedimentary and anthropogenic input. Cl^- behaves more conservatively than Na^+ and Cl^- peaks, caused by the flushing of agricultural and/or urban anthropogenic salt applications or from natural pathways, are not always matched by Na^+ . This leads to temporary Cl^- excesses, predominantly in the spring. This retardation of Na^+ is likely caused by cation exchange. During low water stands, when a greater portion of the water is supplied by the uplands, Na^+ exceeds Cl^- due to silicate weathering.

Mass balances based on concentrations, discharge and isotopic constraints yield the flux of sulfate and strontium from the Ottawa River to be 5.8×10^9 and $3.4 \times 10^7 \text{mol/a}$, respectively, representing 0.18 and 0.16% of the global riverine budgets. Most of the sulfur originates from atmospheric inputs, with less than 10% coming from the dissolution of evaporite minerals, from pore water leaching the Paleozoic and Quaternary lowland sediments, and possibly from direct industrial sulfur contributions. Strontium is purely of

geogenic origin with its concentration and isotopes reflecting either the old silicate or the young carbonate terrains or a mix of these two end-members.

Principal component analysis identifies two major and three minor controls on the chemistry of the waters in the Ottawa River basin. The dominant control is carbonate weathering and to a lesser degree anthropogenic pollution (road salting, agricultural and municipal discharges) both predominant in the lowlands. The second major control is also predominantly geogenic and represents the chemical and physical changes associated with a shift from the silicate shield to the carbonate lowlands. The minor controls are roughly equal in importance and are represented by the shift from highly resistant plutonic bedrock to less resistant metamorphic bedrock, the hydrological cycle, and by soil productivity.

Waters of the Ottawa River basin plot in all the categories of the river classification schemes of Gibbs (1970) and Stallard and Edmond (1983), yet genetic processes assumed to generate these categories do not always conform with those encountered in the present study. Recent glaciation and marine inundation are at least partly responsible for the genetic discrepancies, illuminating the strong link between geological history and river chemistry.

Ultimately, geology and geological history has led to the physiochemical characteristics of the present day Ottawa River basin. These characteristics and their interaction with present day climate are at the centre of the interrelationships between drainage patterns, soil development, biomass accumulation, water balances, and human population, which in turn control water chemistry. Good understanding of the geology and geological history of river basins yields, therefore, fruitful insights into the origins of river waters and their chemistry, and ultimately into the global exogenic cycle.

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Table A1: Location and Date of Samples.

¹ r = river sample; t = tributary sample; m = monitoring sample

Sample No	Latitude	Longitude	Date sampled	Sample type ¹	Location
1	47.6440	-76.4461	18-Sep-91	r	Ottawa River, Headwaters
2	47.6128	-77.3072	19-Sep-91	r	Ottawa River, Lac Dozois
3	47.8442	-77.5500	20-Sep-91	r	Ottawa River, Lac Granet
4	47.7683	-78.3106	21-Sep-91	r	Ottawa River, Rapide Sept
5	47.6556	-78.8165	20-Sep-91	r	Ottawa River, Lac Simard
6	47.6222	-79.4566	20-Sep-91	r	Ottawa River, Notre Dame du Nord
7	46.7322	-79.1039	23-Sep-91	r	Ottawa River, Temiskaming
8	46.2646	-78.2998	26-Sep-91	r	Ottawa River, Duex Riviere
9	46.1833	-77.6978	25-Sep-91	r	Ottawa River, Rolphton
10	45.7768	-76.9845	27-Sep-91	r	Ottawa River, Pembroke
11	45.5649	-76.6317	28-Sep-91	r	Ottawa River, Portage du Fort
12	45.4962	-76.1694	29-Sep-91	r	Ottawa River, Quyon
13	45.3984	-75.6618	05-Sep-91	r	Ottawa River, Champlain Bridge
14	45.5102	-75.3179	30-Sep-91	r	Ottawa River, Cumberland
15	45.6159	-74.4872	07-Sep-91	r	Ottawa River, Hawkesbury
16	45.4695	-73.9623	15-Sep-91	r	Ottawa River, Carrillon
17	47.7016	-76.5176	18-Sep-91	t	Camachigama
18	47.9566	-78.6546	21-Sep-91	t	Kenojevis
19	47.6162	-79.5065	22-Sep-91	t	Blanche
20	47.1805	-79.4890	22-Sep-91	t	Montreal
21	47.0975	-79.3775	23-Sep-91	t	Kipawa
22	46.3343	-78.7501	23-Sep-91	t	Mattawa
23	45.8956	-77.2704	27-Sep-91	t	Petawawa
24	45.9021	-76.9147	28-Sep-91	t	Noire
25	45.8318	-76.7087	28-Sep-91	t	Coulange
26	45.4126	-76.2977	29-Sep-91	t	Madawaska
27	45.4144	-76.2103	29-Sep-91	t	Mississippi
28	45.4093	-75.5939	04-Sep-91	t	Rideau
29	45.4488	-75.6302	06-Sep-91	t	Gatineau
30	45.6047	-75.0370	06-Sep-91	t	Petite Nation
31	45.5612	-74.9973	09-Sep-91	t	South Nation
32	45.6726	-74.5759	07-Sep-91	t	Rouge
33	45.6155	-74.2608	08-Sep-91	t	Nord
34	45.4921	-74.1785	08-Sep-91	t	Rigaud
35	47.6440	-76.4461	23-May-92	r	Ottawa River, Headwaters
36	47.6128	-77.3072	24-May-92	r	Ottawa River, Lac Dozois
37	47.7683	-78.3106	24-May-92	r	Ottawa River, Rapide Sept
38	47.6556	-78.8165	26-May-92	r	Ottawa River, Lac Simard
39	47.6222	-79.4566	26-May-92	r	Ottawa River, Notre Dame du Nord
40	46.7322	-79.1039	26-May-92	r	Ottawa River, Temiskaming
41	46.3778	-78.7233	27-May-92	r	Ottawa River, Mattawa Dam
42	46.1833	-77.6978	27-May-92	r	Ottawa River, Rolphton
43	45.7768	-76.9845	28-May-92	r	Ottawa River, Pembroke
44	45.5649	-76.6317	28-May-92	r	Ottawa River, Portage du Fort

Table A1: Location and Date of Samples.

¹ r = river sample; t = tributary sample; m = monitoring sample

Sample No	Latitude	Longitude	Date sampled	Sample type ¹	Location
45	45.4962	-76.1694	01-Jun-92	r	Ottawa River, Quyon
46	45.3984	-75.6618	31-May-92	r	Ottawa River, Champlain Bridge
47	45.5102	-75.3179	22-May-92	r	Ottawa River, Cumberland
48	45.6416	-74.9194	22-May-92	r	Ottawa River, Montebello
49	45.6159	-74.4872	22-May-92	r	Ottawa River, Hawkesbury
50	45.5700	-74.3928	22-May-92	r	Ottawa River, Carillon
51	47.7016	-76.5176	23-May-92	t	Camachigama
52	47.9566	-78.6546	25-May-92	t	Kenojevis
53	47.6162	-79.5065	25-May-92	t	Blanche
54	47.1805	-79.4890	25-May-92	t	Montreal
55	47.0975	-79.3775	26-May-92	t	Kipawa
56	46.3343	-78.7501	26-May-92	t	Mattawa
57	46.2250	-77.8500	27-May-92	t	Dumoine
58	45.8956	-77.2704	27-May-92	t	Petawawa
59	45.9021	-76.9147	28-May-92	t	Noire
60	45.8318	-76.7087	28-May-92	t	Coulonge
61	45.5666	-76.6666	29-May-92	t	Bonnechere
62	45.4126	-76.2977	29-May-92	t	Madawaska
63	45.4144	-76.2103	29-May-92	t	Mississippi
64	45.4093	-75.5939	31-May-92	t	Rideau
65	45.4488	-75.6302	01-Jun-92	t	Gatineau
66	45.5250	-75.4361	11-Jun-92	t	Lievre
67	45.6047	-75.0370	22-May-92	t	Petite Nation
68	45.5612	-74.9973	21-May-92	t	South Nation
69	45.6726	-74.5759	22-May-92	t	Rouge
70	47.6440	-76.4461	29-Sep-92	r	Ottawa River, Headwaters
71	47.6128	-77.3072	29-Sep-92	r	Ottawa River, Lac Dozois
72	47.7683	-78.3106	29-Sep-92	r	Ottawa River, Rapide Sept
73	47.6556	-78.8165	30-Sep-92	r	Ottawa River, Lac Simard
74	47.6222	-79.4566	30-Sep-92	r	Ottawa River, Notre Dame du Nord
75	46.7322	-79.1039	30-Sep-92	r	Ottawa River, Temiskaming
76	46.3778	-78.7233	30-Sep-92	r	Ottawa River, Mattawa Dam
77	46.1833	-77.6978	01-Oct-92	r	Ottawa River, Rolphston
78	45.7768	-76.9845	01-Oct-92	r	Ottawa River, Pembroke
79	45.5649	-76.6317	01-Oct-92	r	Ottawa River, Portage du Fort
80	45.4962	-76.1694	01-Oct-92	r	Ottawa River, Quyon
81	45.3984	-75.6618	01-Oct-92	r	Ottawa River, Champlain Bridge
82	45.5102	-75.3179	24-Sep-92	r	Ottawa River, Cumberland
83	45.6416	-74.9194	24-Sep-92	r	Ottawa River, Montebello
84	45.6159	-74.4872	24-Sep-92	r	Ottawa River, Hawkesbury
85	45.5700	-74.3928	24-Sep-92	r	Ottawa River, Carillon
86	45.4488	-75.6302	24-Sep-92	t	Gatineau
87	45.5612	-74.9973	23-Sep-92	t	South Nation
88	45.6726	-74.5759	24-Sep-92	t	Rouge

Table A1: Location and Date of Samples.

¹ r = river sample; t = tributary sample; m = monitoring sample

Sample No	Latitude	Longitude	Date sampled	Sample type ¹	Location
89	45.4695	-73.9623	17-Apr-93	m	Ottawa River, Carillon
90	45.4695	-73.9623	17-May-93	m	Ottawa River, Carillon
91	45.4695	-73.9623	17-Jun-93	m	Ottawa River, Carillon
92	45.4695	-73.9623	03-Aug-93	m	Ottawa River, Carillon
93	45.4695	-73.9623	31-Aug-93	m	Ottawa River, Carillon
94	45.4695	-73.9623	24-Sep-93	m	Ottawa River, Carillon
95	45.4695	-73.9623	08-Oct-93	m	Ottawa River, Carillon
96	45.4695	-73.9623	02-Nov-93	m	Ottawa River, Carillon
97	45.4695	-73.9623	05-Dec-93	m	Ottawa River, Carillon
98	45.4695	-73.9623	06-Jan-94	m	Ottawa River, Carillon
99	45.4695	-73.9623	07-Feb-94	m	Ottawa River, Carillon
100	45.4695	-73.9623	06-Mar-94	m	Ottawa River, Carillon
101	45.4695	-73.9623	14-Apr-94	m	Ottawa River, Carillon
102	45.4695	-73.9623	22-Apr-94	m	Ottawa River, Carillon
103	45.4695	-73.9623	11-May-94	m	Ottawa River, Carillon

Appendix A

Table A2: Chemical analyses for the Ottawa River and its major tributaries (1991-94). The shaded bar contains detection limits.

No	River Location	Temp °C	Cond. pH µm/cm	DO µmol/L	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	PO ₄ ³⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Si	Fe	Mn	Sr ²⁺	Al	Ba ²⁺	Charge %	pCO ₂ ppm	Calcite DIC S.I. µmol/L		
1	OR@ Headwaters	15.0	7.1	23	319	54	25	50	25	0.2	59.5	30.8	40	6	77	5.0	0.27	0.27	3.1	0.70	6	246	-3.4	65
2	OR@ Lac Dozols	16.0	6.6	22	406	52	39	52	34	0.5	48.5	28.3	43	5	57	3.6	0.34	0.24	2.4	0.38	-7	437	-3.7	71
3	OR @ Lac Granet	16.0	7.1	22	388	44	31	57	31	0.4	49.0	29.0	41	20	57	2.9	0.32	0.24	2.0	0.56	-1	203	-3.6	53
4	OR@ Rapide Sept	16.0	6.9	20	325	46	39	57	41	0.3	47.7	27.7	40	13	54	3.6	0.25	0.22	4.5	0.72	-8	345	-3.8	61
5	OR@ Lac Simard	14.5	7.1	38	450	88	39	82	28	0.2	87.8	44.4	56	21	67	3.8	0.23	0.30	4.0	0.39	3	363	-3.0	105
6	OR@ Notre Dame du Nord	15.0	7.2	43	431	112	48	88	41	0.3	100.9	50.8	59	16	62	3.4	0.15	0.31	4.5	0.32	0	434	-2.8	132
7	OR@ Temiskaming	16.0	7.6	70	356	340	73	87	41	0.4	196.2	90.3	73	25	66	1.9	0.07	0.41	4.4	1.11	4	474	-1.5	361
8	OR@ Deux Rivières	15.5	7.3	71		324	73	84	97	0.6	112.9	71.8	63	18	65	1.3	0.07	0.50	1.3	0.18	-19	938	-2.1	366
9	OR@ Rolphton	17.0	7.3	68	325	294	79	109	134	1.1	186.8	83.1	109	20	62	1.6	0.07	0.42	3.0	0.12	-4	868	-1.9	331
10	OR@ Pembroke	13.5	7.6	67	388	304	71	107	109	0.2	177.4	81.9	101	13	53	1.3	0.07	0.42	3.7	0.12	-5	420	-1.7	324
11	OR@ Portage du Fort	13.9	7.9	69	400	310	102	100	97	0.2	177.6	80.2	117	16	55	1.5	0.07	0.44	2.7	0.12	-4	231	-1.4	321
12	OR@ Quyon	10.6	7.7	81	469	370	76	105	78	0.3	202.2	87.9	114	25	55	1.2	0.07	0.49	2.0	0.14	-1	374	-1.5	390
13	OR@ Champlain Bridge	22.0	7.9	76	519	420	135	107	22	1.2	205.9	91.1	125	19	58	1.5	0.07	0.57	1.5	0.13	-3	334	-1.1	433
14	OR@ Cumberland	12.8	7.7	83	438	322	73	102	41	0.3	193.9	78.6	142	26	53	1.7	0.11	0.57	2.6	0.16	6	366	-1.6	340
15	OR@ Hawkesbury	23.0	7.5	75	300	340	175	100	91	0.5	202.0	81.4	160	31	56	1.6	0.11	0.64	1.2	0.17	-4	628	-1.5	363
16	OR@ Oka	19.5	7.8	78	363	420	155	103	59	4.6	215.9	87.9	174	27	56	1.6	0.23	0.68	0.4	0.36	-2	446	-1.2	438
17	Camachigama	15.0	7.3	22	325	60	31	38	91	0.2	54.8	33.5	38	12	86	4.6	0.34	0.22	2.9	1.13	-6	169	-3.2	68
18	Kenojevis	14.0	7.6	170	363	619	276	333	53	0.1	508.2	154.8	269	29	88	5.9	1.07	0.79	5.5	0.27	0	902	-0.9	663
19	Blanche	14.0	7.2	150	338	1087	141	105	25	0.7	518.7	227.4	147	22	91	3.4	0.15	1.03	5.3	0.21	6	3977	-1.1	1275
20	Montreal	17.0	8.0	70	431	360	68	87	44	0.6	208.6	91.9	71	5	62	2.1	0.07	0.38	4.7	0.21	2	212	-1.1	370
21	Kipawa	16.0	7.1	30	375	50	42	78	34	0.4	65.2	32.3	42	12	47	0.3	0.07	0.33	2.3	0.18	-6	236	-3.4	60
22	Mattawa	17.0	7.6	52	413	218	76	86	19	0.6	121.3	68.1	91	23	51	1.1	0.17	0.49	2.1	0.17	1	315	-1.9	232
23	Petawawa	14.5	7.6	48	400	280	28	115	12	0.2	191.5	86.7	111	20	62	1.8	0.13	0.42	3.7	0.32	11	401	-1.7	289
24	Noire	11.0	7.8	46	406	206	31	71	12	0.1	121.8	44.8	47	5	63	3.8	0.48	0.54	2.2	0.11	-1	162	-1.8	215
25	Coulange	10.5	8.0	52	475	256	23	72	12	0.3	141.7	48.0	60	13	63	2.8	0.25	0.65	2.0	0.12	2	129	-1.5	284
26	Madawaska	13.1	8.7	130	394	921	93	105	9	0.7	471.6	142.7	95	25	49	0.8	0.07	0.98	1.0	0.21	5	108	0.3	942
27	Mississ/ppi	11.9	8.7	220	438	1698	166	118	19	0.4	736.2	306.8	158	27	25	0.3	0.07	1.65	0.4	0.74	4	177	0.8	1728
28	Rideau	23.0	8.4	297	369	1958	584	155	22	0.7	867.1	512.1	563	28	15	1.7	0.13	2.70	0.6	0.33	8	524	0.7	1998
29	Gatineau	22.1	7.0	41	469	190	31	63	37	4.9	123.7	42.3	53	18	55	2.1	0.31	0.41	0.4	0.41	1	1097	-2.5	230
30	Petite Nation	21.0	8.1	108	469	599	209	122	62	8.6	345.8	104.8	204	77	74	3.1	0.11	0.97	0.4	0.19	2	333	-0.5	615
31	South Nation	21.0	9.2	381	406	2038	1213	244	34	1.1	869.8	487.9	1494	84	58	0.6	0.07	3.34	0.4	0.24	6	90	1.5	2164
32	Rouge	21.0	8.1	43	419	200	169	70	47	0.4	132.3	40.3	86	14	76	3.4	0.17	0.46	1.3	0.18	-11	101	-1.4	205
33	Nord	21.8	8.3	316	344	1099	1523	183	56	10.5	547.5	237.1	1549	56	63	0.9	0.29	1.85	0.4	1.15	2	390	0.1	1122
34	Rigaud	22.8	8.5	425	463	2578	987	365	312	15.8	1223.4	568.5	987	201	132	1.2	0.13	14.68	0.4	0.29	2	522	1.1	2632
35	OR@ Headwaters	9.0	6.2	20	556	18	54	38	7		46.9	20.9	30	7	72	3.4	0.45	0.15	5.7	0.12	5	633	-5.0	53

Appendix A

Table A2: Chemical analyses for the Ottawa River and its major tributaries (1991-94). The shaded bar contains detection limits.

No	River Location	Temp °C	pH	Cond. µs/cm	µmol/L												Charge		pCO ₂ Calcite DIC					
					DO	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	PO ₄ ³⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Si	Fe	Mn	Sp ²⁺	Al	Ba ²⁺	%	ppm	S.I.	µmol/L
36	OR@ Lac Dozois	8.6	6.5	22	593	24	73	43	9		46.7	25.4	43	20	85	2.1	0.50	0.17	4.4	0.12	4	402	-4.6	47
37	OR@ Rapide Sept	11.5	6.1	26	618	26	69	47	8		50.0	26.6	41	13	74	3.0	0.45	0.17	6.0	0.54	3	1132	-4.8	84
38	OR@ Lac Simard	17.2	6.8	45	664	100	91	86	9		118.8	50.5	68	20	78	3.1	0.50	0.23	6.4	0.12	7	895	-3.1	136
39	OR@ Notre Dame du Nord	12.6	7.0	50	776	138	92	79	11		119.4	57.3	69	24	80	3.6	0.43	0.25	8.6	0.39	6	805	-2.8	177
40	OR@ Temiskaming	14.9	7.1	60	788	210	97	76	9		160.9	71.8	68	20	82	3.3		0.31	7.6	0.13	8	1001	-2.4	256
41	OR@ Mattawa Dam	13.1	7.0	60	670	182	126	95	11		144.7	63.7	94	20	78	2.8	0.18	0.29	5.7	0.31	2	1143	-2.7	237
42	OR@ Robitton	15.5	6.7	50	707	136	118	85	8		118.9	52.8	79	20	80	2.3	0.21	0.28	6.1	0.17	1	1758	-3.1	215
43	OR@ Pembroke	16.8	7.0	60	671	170	135	88	10		139.0	63.3	99	20	81	2.2	0.23	0.32	4.7	0.21	3	1121	-2.7	218
44	OR @ Portage du Fort	17.7	6.9	60	628	182	155	88	9		142.5	60.3	103	17	80	2.0	0.20	0.33	4.9	0.13	1	1244	-2.6	234
45	OR@ Quyon	21.9	7.1	60	598	246	153	88	9		152.5	64.3	102	23	78	2.0	0.15	0.36	5.0	0.13	-2	1178	-2.2	289
46	OR@ Champlain Bridge	15.2	7.4	74	591	296	175	90	15		211.9	78.8	104	24	77	2.0		0.44	3.5	0.15	4	761	-1.9	330
47	OR@ Cumberland	23.2	7.4	70	676	316	142	85	11		202.0	87.7	56	17	75	2.0	0.21	0.47		0.24	1	809	-1.7	345
48	OR@ Montebello	21.5	7.3	80	659	330	175	86	7		209.2	94.0	67	26	71	2.2	0.23	0.52	2.3	0.12	1	1015	-1.8	368
49	OR@ Hawkesbury	20.4	7.4	80	613	294	132	87	8		210.0	93.3	60	20	75	2.0	0.25	0.51	2.1	0.16	6	707	-1.7	321
50	OR@ Carillon	27.1	7.2	79	651	336	194	91	12		221.8	79.9	126	20	76	1.6	0.27	0.49		0.15	2	1376	-1.7	360
51	Carnachigama	11.2	6.4	20	611	20	54	36	8		49.4	24.4	30	10	77	2.9	0.43	0.14		0.12	10	425	-4.7	42
52	Kenojévis	13.3	7.2	117	526	256	223	241	9		333.7	101.4	149	28	74	3.9	0.72	0.42	9.3	0.13	4	846	-1.9	297
53	Blanche	13.2	8.0	130	614	661	201	105	7		380.1	157.1	150	26	72	2.0	0.13	0.67	5.5	0.12	7	346	-0.6	681
54	Montreal	12.8	7.5	661	328	93	79	9		228.3	86.3	57	14	76	0.9		0.23	3.1	0.16		9	619	-1.7	358
55	Kipawa	13.5	6.7	30	714	28	61	47	10		44.7	29.6	49	20	79	2.1	0.35	0.25	4.1	0.13	6	353	-4.3	45
56	Mattawa	15.3	7.2	50	613	130	93	72	6		107.0	53.3	84	24	59	1.1		0.33	2.2	0.15	7	451	-2.6	150
57	Dumoine	18.3	6.4	30	648	42	45	63	9		66.4	28.0	43	15	82	1.3	0.18	0.24	4.5	0.14	6	981	-4.1	82
58	Petawawa	15.4	7.0	40	594	116	116	78	6		104.1	58.0	55	14	76	1.9	0.19	0.34	2.8	0.19	0	734	-3.0	149
59	Noire	18.0	6.9	40	586	154	45	67	11		119.2	37.9	51	19	94	3.4	0.50	0.40	3.4	0.16	6	1107	-2.8	200
60	Coulange	18.4	6.9	35	686	88	45	63	8		99.7	32.4	43	19	70	2.1	0.22	0.37	4.1	0.15	10	636	-3.1	114
61	Bonnechere	23.6	8.0	170	626	1179	414	117	11		495.3	214.6	184	37	71	0.8		0.89	3.2	0.27	-6	837	-0.1	1213
62	Madawaska	19.7	7.7	120	613	649	168	100	11		401.5	112.8	86	23	76	0.7		0.63	2.8	0.18	5	891	-0.9	686
63	Mississippi	21.1	8.2	220	557	1619	266	112	9		759.3	258.5	148	34	37	0.3		1.20	3.1	0.36	2	684	0.3	1655
64	Rideau	16.3	8.2	380	486	2458	1132	158	8		1075.4	502.6	572	43	18	0.6	0.19	2.04	8.4	0.37	-2	886	0.6	2512
65	Gatineau	17.1	7.2	50	611	196	117	56	8		160.0	44.2	59	18	70	1.6	0.29	0.37	3.7	0.10	6	730	-2.3	227
66	Rivière du Lièvre	24.7	7.3	50	579	220	111	54	12		172.7	35.8	55	16	68	1.6	0.26	0.32	2.2	0.22	4	776	-2.0	247
67	Petite Nation	21.2	7.6	66	663	300	115	80	10		204.7	65.3	38	21	60	1.5	0.13	0.47		0.14	1	517	-1.6	320
68	South Nation	25.7	8.4	564	546	3197	1616	508	14		1529.0	823.3	865	82	28	0.7	0.10	4.49	10.5	5.10	-3	852	1.2	3262
69	Rouge	22.0	7.2	41	636	162	130	56	9		110.1	37.7	38	15	73	1.8	0.10	0.33		0.16	-8	677	-2.5	187
70	OR@ Headwaters	9.9	7.1	20	609	18	28				46.5	20.2	26	10	92	5.1	0.33	0.20	7.6	0.08	5	77	-4.1	22

Appendix A

Table A2: Chemical analyses for the Ottawa River and its major tributaries (1991-94). The shaded bar contains detection limits.

No	River Location	Temp		Cond.		µmol/L												Charge		pCO ₂		Calcite DIC			
		°C	pH	µS/cm	µmol/L	DO	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	PO ₄ ³⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Si	Fe	Mn	Sr ²⁺	Al	Ba ²⁺	%	ppm	S.I.	µmol/L
71	OR@ Lac Dozois	10.3	6.6	20	584	50	47	61				43.7	21.7	36	12	70	1.9	0.10	0.20	4.0	0.10	-10	711	-4.2	88
72	OR@ Rapide Sept	9.8	6.8	20	600	56	28															-4	1124	-3.4	82
73	OR@ Lac Simard	10.2	6.7	40	628	102	61	97				92.2	35.7	56	19	81	4.0	0.25	0.25	7.5	0.09	-4	345	-3.0	108
74	OR@ Notre Dame du Nord	10.5	7.2	40	786	90	57	98				85.9	38.3	51	16	71	2.7	0.10	0.23	7.2	0.07	-2	1841	-2.2	441
75	OR@ Terniskaming	11.9	7.1	70	644	358	53	110				184.4	70.3	72	25	88	2.2	0.09	0.38	7.3	0.12	-3	4710	-2.6	591
76	OR@ Mattawa Dam	11.5	6.6	70	513	350	84	133				199.1	72.8	86	20	93	2.8	0.12	0.37	9.1	0.16	-1	2280	-2.5	402
77	OR@ Rolphaton	12.7	6.9	80	494	280	89	125				175.7	69.8	110	17	80	2.5	0.28	0.35	5.9	0.12	3	2455	-2.5	395
78	OR@ Pembroke	14.0	6.8	65	583	280	89	107				171.7	73.7	107	20	88	2.2	0.13	0.33	3.4	0.11	-5	2180	-2.2	434
79	OR@ Portage du Fort	14.9	7.0	80	569	336	140	144				198.4	66.5	129	31	94	13.9	0.23	0.42	5.2	0.17	-6	1585	-2.4	354
80	OR@ Quyon	14.0	7.0	70	626	280	91	135				162.7	61.4	92	22	89	7.1	0.14	0.43	5.6	0.15				364
81	OR@ Champlain Bridge	15.0	7.3	80	614	322	111																		
82	OR@ Cumberland	18.7	7.3	90	572	430	206	108				224.5	84.4	118	15	62	2.0	0.07	0.59	3.0	0.13	-6	1480	-1.7	489
83	OR@ Montebello	19.5	7.2	90	531	450	63	107				228.4	79.6	146	22	65	1.9	0.09	0.63	3.3	0.15	4	1655	-1.7	515
84	OR@ Hawkesbury	14.0	7.5	90	528	370	499	104				218.8	74.9	147	27	81	1.9	0.10	0.56	3.9	0.12	-17	710	-1.6	403
85	OR@ Carillon	16.6	7.2	90	509	410	158	108				220.3	75.4	146	20	62	1.7	0.03	0.59	2.5	0.12	-2	1702	-1.9	483
86	Gatineau	16.8	7.0	50	647	284	66	64				164.7	44.7	56	5	63	2.0	0.13	0.41	2.0	0.10	0	1594	-2.3	352
87	South Nation	13.0	8.2	650	478	3277	1473	453				1189.9	623.0	1879	122	90	0.7	0.11	4.15	12.5	0.32	0	1239	0.7	3354
88	Rouge	14.2	7.2	40	688	128	75	64				97.7	26.5	58	10	84	3.3	0.13	0.28	5.5	0.08	-2	438	-2.7	148
89	OR@ Carillon	9.8	7.0	80	688	534	141	94	5			337.3	125.7	159	18	74	1.8	0.20	0.68		0.42	12	2803	-1.8	686
90	OR@ Carillon	14.6	7.4	900	594	629	85	75	3			262.5	99.6	113	15	59	1.8	0.16	0.48		0.71	-1	1534	-1.4	701
91	OR@ Carillon	24.1	7.1	110	593	448	113	74	10			243.5	89.3	120	21	52	2.3	0.04	0.46		1.70	6	2105	-1.7	519
92	OR@ Carillon	25.8	7.3	110	613	376	96	100	2			240.5	86.8	132	17	53	1.6	0.05	0.43		0.68	9	1257	-1.6	418
93	OR@ Carillon	24.6	7.2	85	494	380	85	85	2			228.5	84.1	145	12	58	1.2	0.09	0.52		0.73	10	1502	-1.7	431
94	OR@ Carillon	16.6	7.2	90	509	410	102	108	3			220.6	76.9	140	18	56	1.4	0.13	0.57		0.54	2	1702	-1.9	483
95	OR@ Carillon	12.0	7.1	100	600	426	121	103	3			228.5	83.1	135	28	67	1.3	0.09	0.52		0.48	2	1867	-2.0	520
96	OR@ Carillon	8.9	6.9	100	563	364	124	95	3			255.0	96.4	131	20	71	1.7	0.11	0.52		0.33	11	2328	-2.2	494
97	OR@ Carillon	5.2	7.2	120	638	589	121	97	21			318.4	128.4	158	23	78	2.2	0.11	0.66		0.46	8	1802	-1.7	711
98	OR@ Carillon	2.5	6.9	100	600	480	175	94	6			235.5	87.6	157	24	89	2.2	0.11	0.47		0.25	-1	3013	-2.3	693
99	OR@ Carillon	2.7	6.3	100	588	440	113	91	5			239.0	88.9	138	25	90	3.0	0.16	0.48		0.14	5	12358	-2.9	1307
100	OR@ Carillon	3.9	6.5	110	644	480	133	88	7			234.0	88.8	140	17	85	3.0	0.18	0.43		0.14	1	8208	-2.7	1031
101	OR@ Carillon	5.1	7.5	144	763	859	181	90	7			328.1	123.8	158	36	87	6.1	0.25	0.80		0.35	-6	1420	-1.2	951
102	OR@ Carillon	7.4	7.0	130	794	779	130	106	6			356.3	139.9	136	30	73	4.8	0.20	0.78		0.57	1	3718	-1.6	999
103	OR@ Carillon	12.3	7.2	125	663	579	118	90	4			270.2	110.7	111	20	55	2.0	0.15	0.51		0.60	1	2222	-1.69	690

Table A3: Isotope analyses for the Ottawa River and its major tributaries (1991-94). The shaded bar contains precision ratings for the mass spectrometry (2σ).

No.	Location	$\delta^{18}\text{O} \text{ ‰}$ SMOW	$\delta\text{D} \text{ ‰}$ SMOW	$\delta^{13}\text{C} \text{ ‰}$ PDB	$\delta^{34}\text{S} \text{ ‰}$ CDT	$^{87}\text{Sr}/^{86}\text{Sr}$
1	Ottawa River, Headwaters	-10.7	-79	-16.5		0.71123
2	Ottawa River, Lac Dozois	-11.1	-73	-15.5		0.71291
3	Ottawa River, Lac Granet	-11.0	-85	-16.2	4.6	0.71475
4	Ottawa River, Rapide Sept	-11.0	-86	-17.4		0.71521
5	Ottawa River, Lac Simard	-11.1	-86	-10.5	3.9	0.71643
6	Ottawa River, Notre Dame du Nord	-11.2	-86	-11.6	3.8	0.71736
7	Ottawa River, Temiskaming	-11.2	-89	-10.1	4.1	0.71543
8	Ottawa River, Duex Riviere	-11.0	-87	-11.2	4.3	0.71525
9	Ottawa River, Rolphton	-11.7	-85	-11.4	4.6	0.71477
10	Ottawa River, Pembroke	-11.2	-99	-8.6	4.6	0.71504
11	Ottawa River, Portage du Fort	-10.9	-82	-10.3	4.7	0.71441
12	Ottawa River, Quyon	-10.5	-81	-8.4	4.9	0.71357
13	Ottawa River, Champlain Bridge	-9.7	-77	-9.5	5.1	0.71312
14	Ottawa River, Cumberland	-9.8	-81	-9.4	5.8	0.71195
15	Ottawa River, Hawkesbury	-10.2	-80	-11.3	5.1	0.71165
16	Ottawa River, Carrillon	-10.1	-77	-10.4	5.9	0.71145
17	Camachigama	-10.7	-80	-15.4		0.71445
18	Kenojevis	-10.2	-82	-9.5	2.3	0.71702
19	Blanche	-10.3	-80	-10.0	5.8	0.71318
20	Montreal	-11.6	-87	-9.4		0.71500
21	Kipawa	-9.3	-77	-10.3	5.0	0.71536
22	Mattawa	-9.1	-73	-9.2	5.4	0.71352
23	Petawawa	-9.1	-71	-10.0	6.1	0.71258
24	Noire	-9.2	-72	-9.0	5.8	0.70977
25	Coulonge	-9.2	-75	-7.0	5.8	0.70927
26	Madawaska	-8.9	-72	-7.6	6.1	0.70928
27	Mississippi	-10.4	-83	-8.1	6.5	0.70961
28	Rideau	-5.1	-50	-7.2		0.70946
29	Gatineau	-10.5	-80		5.8	0.71061
30	Petite Nation	-8.7	-69	-8.9	7.1	0.71056
31	South Nation	-8.6	-68	-9.3	5.7	0.71026
32	Rouge	-9.3	-74	-7.9	6.1	0.71123
33	Nord	-9.3	-72	-8.8	7.7	0.70825
34	Rigaud	-8.1	-58	-11.7	12.1	0.70916
35	Ottawa River, Headwaters	-12.7	-91	-17.1		0.71098
36	Ottawa River, Lac Dozois	-12.4	-91	-16.0		
37	Ottawa River, Rapide Sept	-11.9	-87	-17.3		0.71604
38	Ottawa River, Lac Simard	-12.3	-88	-12.8	3.4	
39	Ottawa River, Notre Dame du Nord	-12.2	-92	-11.7	3.8	0.71828
40	Ottawa River, Temiskaming	-11.4	-86	-10.6	4.3	0.71551
41	Ottawa River, Mattawa Dam	-11.4	-84	-12.2	4.2	
42	Ottawa River, Rolphton	-11.5	-87	-12.1	3.3	

Table A3: Isotope analyses for the Ottawa River and its major tributaries (1991-94). The shaded bar contains precision ratings for the mass spectrometry (2σ).

No.	Location	$\delta^{18}\text{O} \text{ ‰}$ SMOW	$\delta\text{D} \text{ ‰}$ SMOW	$\delta^{13}\text{C} \text{ ‰}$ PDB	$\delta^{34}\text{S} \text{ ‰}$ CDT	$^{87}\text{Sr}/^{86}\text{Sr}$
43	Ottawa River, Pembroke	-11.4	-86	-11.4	4.7	
44	Ottawa River, Portage du Fort	-11.5	-86	-11.1	4.7	0.71335
45	Ottawa River, Quyon	-11.5	-85		4.7	0.71305
46	Ottawa River, Champlain Bridge	-11.3	-85	-9.5	5.0	0.71192
47	Ottawa River, Cumberland	-11.6	-85	-9.8	5.0	0.71114
48	Ottawa River, Montebello	-11.4	-84	-7.3	5.1	0.71110
49	Ottawa River, Hawkesbury	-11.1	-83	-9.8	4.9	0.71103
50	Ottawa River, Carillon	-11.4	-83	-10.0	5.1	0.71097
51	Camachigama	-12.2	-86	-16.9		
52	Kenojevis	-12.1	-90	-11.3	2.3	
53	Blanche	-11.9	-90	-9.7	4.5	0.70938
54	Montreal	-12.2	-91	-9.4	4.7	0.71286
55	Kipawa	-10.4	-81	-10.4	4.8	
56	Mattawa	-10.8	-80	-7.7		
57	Dumoine	-11.2	-84	-12.8	4.3	0.71418
58	Petawawa	-10.8	-81	-10.7	6.2	
59	Noire	-11.3	-82	-11.8	5.8	
60	Coulonge	-11.1	-83	-9.4		
61	Bonnechere	-9.8	-76	-8.1	6.2	0.71072
62	Madawaska	-10.8	-79	-8.5	4.9	
63	Mississippi	-9.9	-75	-7.9	5.8	
64	Rideau	-9.4	-71	-6.6	6.5	0.70950
65	Gatineau	-12.0	-87	-10.9	5.0	0.70993
66	Lievre	-12.0	-87	-10.8	5.3	0.71091
67	Petite Nation	-9.9	-75	-7.3	5.7	
68	South Nation	-10.8	-76	-9.0	2.4	0.70989
69	Rouge	-11.7	-83	-8.2	5.5	0.71047
70	Ottawa River, Headwaters	-9.1	-76			
71	Ottawa River, Lac Dozois	-9.6	-82			
72	Ottawa River, Rapide Sept	-8.7	-81			
73	Ottawa River, Lac Simard	-9.8	-83			
74	Ottawa River, Notre Dame du Nord	-9.8	-82			
75	Ottawa River, Temiskaming	-10.0	-84			
76	Ottawa River, Mattawa Dam	-9.9	-83			
77	Ottawa River, Rolphston	-9.6	-82			
78	Ottawa River, Pembroke	-9.4	-79			
79	Ottawa River, Portage du Fort	-9.0	-77			
80	Ottawa River, Quyon	-9.2	-77			
81	Ottawa River, Champlain Bridge	-8.9	-75			
82	Ottawa River, Cumberland	-8.4	-72			
83	Ottawa River, Montebello	-8.6	-75			
84	Ottawa River, Hawkesbury	-8.7	-74			

Table A3: Isotope analyses for the Ottawa River and its major tributaries (1991-94). The shaded bar contains precision ratings for the mass spectrometry (2σ).

No.	Location	$\delta^{18}\text{O} \text{ ‰}$ SMOW	$\delta\text{D} \text{ ‰}$ SMOW	$\delta^{13}\text{C} \text{ ‰}$ PDB	$\delta^{34}\text{S} \text{ ‰}$ CDT	$^{87}\text{Sr}/^{86}\text{Sr}$
85	Ottawa River, Carillon	-8.8	-74			
86	Gatineau	-8.9	-73			
87	South Nation	-7.6	-64			
88	Rouge	-8.7	-65			
89	Ottawa River, Carillon	-11.8	-87	-9.2	4.3	
90	Ottawa River, Carillon	-11.4	-84	-9.3	5.1	
91	Ottawa River, Carillon	-11.2	-84	-10.2	4.8	
92	Ottawa River, Carillon	-10.5	-80	-10.9	4.3	
93	Ottawa River, Carillon	-10.4	-79	-11.5	2.1	
94	Ottawa River, Carillon	-10.0	-77	-12.0	5.4	
95	Ottawa River, Carillon	-10.0	-78	-10.5	5.4	
96	Ottawa River, Carillon	-10.3	-77	-9.2	4.8	
97	Ottawa River, Carillon	-10.6	-80	-9.5	4.7	
98	Ottawa River, Carillon	-11.3	-86	-10.2	4.6	
99	Ottawa River, Carillon	-11.0	-84	-10.9	5.0	
100	Ottawa River, Carillon	-10.8	-84	-10.4	4.6	
101	Ottawa River, Carillon	-11.8	-89	-8.6	5.3	
102	Ottawa River, Carillon	-11.4	-86	-9.4	4.7	
103	Ottawa River, Carillon	-11.0	-82	-9.1	5.3	

Table A4: Trace element analyses for the Ottawa River and its major tributaries (1991).
The shaded bar contains detection limits.

No	River Location	$\mu\text{mol}/1000\text{l}$								
		Cd	Co	Cr	Cu	Ni	Pb	Ti	V	Zn
1	Ottawa River, Headwaters	27	153	154	153	365	236	42	79	96
2	Ottawa River, Lac Dozois	47	153	377	136	255	307	42	79	64
3	Ottawa River, Lac Granet	28	153	154	79	219	151	42	79	80
4	Ottawa River, Rapide Sept	27	153	154	79	136	130	129	79	48
5	Ottawa River, Lac Simard	27	153	154	153	310	130	42	110	128
6	Ottawa River, Notre Dame du Nord	37	153	154	79	136	213	42	79	80
7	Ottawa River, Temiskaming	27	153	198	79	136	130	54	79	32
8	Ottawa River, Deux Riviere	28	153	154	79	136	130	121	79	31
9	Ottawa River, Rolphton	47	153	154	79	136	130	86	79	32
10	Ottawa River, Pembroke	28	153	154	119	136	130	142	202	48
11	Ottawa River, Portage du Fort	27	153	154	79	136	130	50	206	31
12	Ottawa River, Quyon	27	153	154	79	136	130	127	186	31
13	Ottawa River, Champlain Bridge	27	153	185	79	346	132	797	276	48
14	Ottawa River, Cumberland	37	153	154	79	136	130	42	220	96
15	Ottawa River, Hawkesbury	27	153	241	79	136	265	42	162	31
16	Ottawa River, Carrillon	28	153	177	85	136	251	42	298	112
17	Camachigama	37	153	154	136	401	130	42	79	96
18	Kenojevis	28	153	154	153	136	130	90	79	96
19	Blanche	27	153	157	79	136	130	113	258	31
20	Montreal	27	153	154	79	136	130	150	79	32
21	Kipawa	27	153	154	79	136	130	48	79	112
22	Mattawa	27	153	154	79	136	130	42	156	64
23	Petawawa	27	153	154	79	136	130	96	116	32
24	Noire	28	153	154	79	136	130	104	162	31
25	Coulonge	37	153	154	79	136	130	92	198	64
26	Madawaska	27	153	154	79	136	130	52	188	31
27	Mississippi	27	153	154	119	136	130	54	541	48
28	Rideau	28	153	154	255	136	213	42	807	257
29	Gatineau	27	153	154	79	219	189	42	196	31
30	Petite Nation	27	153	154	79	136	130	42	240	321
31	South Nation	37	153	154	221	136	130	42	965	96
32	Rouge	27	153	154	79	328	130	42	148	31
33	Nord	27	153	154	79	219	222	42	461	48
34	Rigaud	28	153	201	79	182	303	42	843	80

Table A5: Trace element analyses for the Ottawa River and its major tributaries (1992). The shaded bar contains detection limits.

No. River Location	$\mu\text{mol}/1000\text{l}$										Y	Cd	In	La 139	Ce 140	Pr 141
	Al	Ti	V	Mn	Fe	Co	Ni	Cu	Zn							
35 Ottawa River, Headwaters	3968	15	5.3	255	3080	4.36	9	13	69.3	1.2	0.89	0.009	1.87	3.14	0.45	0.45
36 Ottawa River, Lac Dozols	3780	11	2.9	291	1988	5.38	19	9	73.4	0.7	1.60	0.009	0.94	1.57	0.22	0.22
37 Ottawa River, Rapide Sept	4299	17	3.7	273	2793	3.61	15	11	73.4	0.9	0.53	0.009	1.22	2.14	0.29	0.29
38 Ottawa River, Lac Simard	4892	40	5.7	273	2578	3.00	19	39	108.6	1.6	1.33	0.009	2.09	3.50	0.47	0.47
39 Ottawa River, Notre Dame du Nord	5448	55	6.3	237	2883	2.53	19	35	103.5	1.7	1.60	0.009	2.23	3.71	0.51	0.51
40 Ottawa River, Temiskaming	4855	56	5.7	55	2543	1.22	17	22	34.1	1.5	1.07	0.009	1.94	2.64	0.45	0.45
41 Ottawa River, Mattawa Dam	3632	40	4.9	127	2346	0.92	19	27	53.5	1.5	0.71	0.009	1.94	2.64	0.46	0.46
42 Ottawa River, Rolphton	3595	30	4.1	146	1934	0.68	15	20	64.4	2.0	0.89	0.009	2.81	3.64	0.67	0.67
43 Ottawa River, Pembroke	2891	21	4.1	146	1828	0.59	14	17	53.5	2.5	1.60	0.009	3.09	3.86	0.77	0.77
44 Ottawa River, Portage du Fort	2817	21	4.9	127	1862	0.54	12	17	41.6	2.2	0.62	0.009	3.09	3.86	0.79	0.79
45 Ottawa River, Quyon	2372	19	5.1	127	1701	0.37	14	17	60.4	2.0	0.71	0.009	2.66	3.36	0.65	0.65
46 Ottawa River, Champlain Bridge	1890	18	5.5	73	1629	0.24	14	22	44.7	1.8	0.89	0.009	2.23	2.64	0.54	0.54
47 Ottawa River, Cumberland	1853	16	5.5	109	1683	4.38	10	19	34.9	1.7	0.44	0.009	2.30	3.00	0.56	0.56
48 Ottawa River, Montebello	1742	19	5.7	127	1755	0.58	12	27	53.7	1.6	3.56	0.009	1.94	2.57	0.47	0.47
49 Ottawa River, Hawkesbury	1816	15	5.5	146	1647	2.29	10	16	37.9	1.7	0.71	0.009	2.09	2.79	0.49	0.49
50 Ottawa River, Carillon	1964	19	5.7	164	1773	1.76	10	17	38.7	1.7	0.62	0.009	2.16	2.86	0.52	0.52
51 Camachigama	3039	9	2.9	218	2471	2.92	12	9	43.9	0.7	0.44	0.009	1.22	2.00	0.29	0.29
52 Kenogvis	5115	63	10.2	364	3384	3.51	26	76	91.6	2.0	1.60	0.017	2.73	4.79	0.60	0.60
53 Blanche	2631	32	10.4	73	1755	1.14	70	42	18.4	1.5	0.80	0.009	1.80	2.79	0.40	0.40
54 Montreal	1705	7	3.9	36	985	0.51	10	19	19.3	1.0	0.44	0.009	1.01	1.14	0.23	0.23
55 Kipawa	1816	3	1.0	36	233	0.29	12	11	55.4	1.0	0.71	0.009	1.37	1.57	0.33	0.33
56 Mattawa	1149	6	2.4	55	1092	0.32	9	11	34.0	2.1	1.51	0.009	2.59	2.64	0.62	0.62
57 Dumoine	2780	8	2.0	127	1164	0.59	9	8	49.4	1.9	0.27	0.009	2.66	3.29	0.67	0.67
58 Petawawa	1223	7	2.6	146	1719	0.22	5	8	40.4	3.1	0.09	0.009	3.60	3.64	0.92	0.92
59 Noire	1594	10	4.1	328	3169	1.58	9	17	24.6	2.0	1.33	0.009	3.02	4.00	0.72	0.72
60 Coulange	2520	12	3.9	146	1952	1.02	9	13	38.6	1.8	0.71	0.009	3.02	4.07	0.70	0.70
61 Bonnechere	371	4	6.7	55	806	0.31	7	19	13.5	0.4	1.16	0.009	0.36	0.50	0.08	0.08
62 Madawaska	371	4	4.1	18	663	0.08	3	13	9.0	0.8	0.18	0.009	0.50	0.43	0.12	0.12
63 Mississippi	371	2	7.9	55	286	0.27	5	9	25.4	0.3	0.62	0.009	0.14	0.21	0.04	0.04

Table A5: Trace element analyses for the Ottawa River and its major tributaries (1992). The shaded bar contains detection limits.

No. River Location	$\mu\text{mol}/1000\text{l}$														Pr 141
	Al	Ti	V	Mn	Fe	Co	Ni	Cu	Zn	Y	Cd	In	La 139	Ce 140	
64 Rideau	371	4	16.7	127	555	0.73	15	25	53.7	0.3	1.16	0.009	0.22	0.21	0.04
65 Gatineau	1779	9	5.1	218	1450	0.53	12	13	39.8	1.7	1.07	0.009	2.88	3.64	0.65
66 Lievre	0	0	0.0	0	0	0.00	0	0	0.0	0.0	0.00	0.000	0.00	0.00	0.00
67 Petite Nation	852	14	4.7	91	1271	2.15	5	13	18.5	1.0	0.53	0.009	1.01	1.21	0.23
68 South Nation	519	10	35.9	55	448	3.53	17	36	11.3	1.0	1.33	0.009	0.58	0.88	0.14
69 Rouge	1594	8	3.3	73	1594	1.88	5	11	32.6	2.0	0.44	0.009	1.94	2.36	0.48
70 Ottawa River, Headwaters	4892	29	7.1	273	5050	3.95	20	14	66.8	1.9	2.58	0.009	2.73	4.64	0.70
71 Ottawa River, Lac Dozols	2372	13	2.8	91	1916	0.90	22	19	72.3	0.4	1.42	0.009	0.65	1.00	0.15
72 Ottawa River, Rapide Sept	3373	24	4.5	200	2829	6.24	28	28	91.3	0.8	10.94	0.009	0.94	1.71	0.23
73 Ottawa River, Lac Simard	4289	53	6.3	182	3134	2.68	31	58	115.9	1.5	4.00	0.009	1.94	3.21	0.46
74 Ottawa River, Notre Dame du Nord	3447	47	6.7	91	2758	10.27	29	47	73.7	1.3	3.91	0.009	1.94	2.86	0.43
75 Ottawa River, Temiskaming	3595	52	7.5	55	2059	2.19	39	55	128.5	1.6	3.65	0.009	2.09	2.79	0.48
76 Ottawa River, Mattawa Dam	3187	41	7.3	109	2471	1.60	43	41	15.8	1.6	4.18	0.009	2.09	3.00	0.51
77 Ottawa River, Rolphston	2298	25	5.9	218	2220	1.71	26	36	91.2	1.8	5.25	0.009	2.30	3.07	0.56
78 Ottawa River, Pembroke	0	0	0.0	0	0	0.00	0	0	0.0	0.0	0.00	0.000	0.00	0.00	0.00
79 Ottawa River, Portage du Fort	2075	23	6.3	146	14969	2.22	172	46	151.3	1.7	4.27	0.009	2.30	2.71	0.54
80 Ottawa River, Quyon	1890	21	6.1	109	7682	1.09	80	39	78.8	1.8	7.38	0.009	2.30	2.79	0.54
81 Ottawa River, Champlain Bridge	0	0	0.0	0	0	0.00	0	0	0.0	0.0	0.00	0.000	0.00	0.00	0.00
82 Ottawa River, Cumberland	927	10	6.3	55	1289	0.63	15	17	33.0	0.9	1.51	0.009	1.01	1.14	0.23
83 Ottawa River, Montebello	1001	20	6.9	55	1253	0.88	12	16	43.9	0.9	1.87	0.009	1.01	1.36	0.25
84 Ottawa River, Hawkesbury	1112	14	8.2	91	1883	2.49	28	36	69.7	1.1	4.72	0.009	1.22	1.57	0.28
85 Ottawa River, Carillon	964	12	8.0	73	1558	1.05	17	27	74.9	1.0	2.58	0.009	1.08	1.43	0.27
86 Gatineau	889	9	3.9	127	1719	0.71	15	13	37.0	0.9	1.16	0.009	1.44	1.71	0.32
87 South Nation	408	8	53.4	91	304	4.82	31	54	45.9	0.9	4.72	0.009	0.43	0.71	0.11
88 Rouge	2854	16	3.7	146	3259	1.68	9	20	49.6	3.9	1.25	0.009	3.31	4.14	0.82

Table A5: Trace element analyses for the Ott River and its major tributaries (1992). The shaded bar contains detection limits.

No. River Location	$\mu\text{mol}/1000\text{l}$													
	Nd 144	Sm 147	Eu 153	Tb 159	Gd 160	Dy 163	Ho 165	Er 166	Tm 169	Yb 174	Lu 175	Pb 208	U 238	
35 Ottawa River, Headwaters	1.67	0.27	0.039	0.025	0.19	0.11	0.024	0.060	0.012	0.057	0.006	1.06	0.03	
36 Ottawa River, Lac Dozols	0.83	0.12	0.026	0.013	0.11	0.05	0.012	0.036	0.006	0.029	0.006	0.87	0.02	
37 Ottawa River, Rapide Sept	1.11	0.18	0.033	0.019	0.15	0.09	0.018	0.060	0.006	0.040	0.006	0.67	0.08	
38 Ottawa River, Lac Simard	1.74	0.31	0.059	0.025	0.22	0.13	0.030	0.078	0.012	0.057	0.011	1.15	0.17	
39 Ottawa River, Notre Dame du Nord	2.01	0.31	0.059	0.031	0.22	0.15	0.030	0.090	0.012	0.069	0.011	1.01	0.17	
40 Ottawa River, Temiskaming	1.67	0.27	0.052	0.031	0.22	0.13	0.024	0.078	0.012	0.057	0.006	0.72	0.20	
41 Ottawa River, Mattawa Dam	1.74	0.31	0.052	0.025	0.21	0.12	0.024	0.084	0.012	0.069	0.011	0.96	0.19	
42 Ottawa River, Rolphton	2.50	0.43	0.065	0.038	0.33	0.18	0.036	0.108	0.012	0.075	0.011	0.91	0.15	
43 Ottawa River, Pembroke	2.65	0.48	0.072	0.050	0.36	0.21	0.042	0.120	0.018	0.098	0.011	0.63	0.15	
44 Ottawa River, Portage du Fort	2.92	0.45	0.072	0.044	0.36	0.19	0.042	0.114	0.018	0.092	0.011	0.72	0.11	
45 Ottawa River, Quyon	2.43	0.41	0.059	0.038	0.28	0.17	0.036	0.108	0.012	0.086	0.011	0.77	0.18	
46 Ottawa River, Champlain Bridge	1.94	0.33	0.052	0.031	0.23	0.14	0.030	0.090	0.012	0.075	0.011	1.01	0.25	
47 Ottawa River, Cumberland	2.08	0.29	0.046	0.031	0.25	0.14	0.030	0.090	0.012	0.080	0.011	0.63	0.24	
48 Ottawa River, Montebello	1.81	0.28	0.046	0.025	0.19	0.13	0.030	0.084	0.012	0.057	0.011	0.82	0.26	
49 Ottawa River, Hawkesbury	1.88	0.28	0.046	0.031	0.20	0.13	0.030	0.090	0.012	0.075	0.011	0.43	0.24	
50 Ottawa River, Carillon	1.94	0.33	0.052	0.031	0.19	0.13	0.030	0.084	0.012	0.075	0.011	0.48	0.29	
51 Camachigama	1.04	0.16	0.026	0.013	0.11	0.06	0.012	0.036	0.006	0.023	0.006	0.82	0.02	
52 Kenogvis	2.29	0.39	0.072	0.038	0.28	0.18	0.036	0.108	0.012	0.086	0.011	1.68	0.27	
53 Blanche	1.46	0.25	0.052	0.025	0.17	0.13	0.024	0.072	0.012	0.063	0.011	0.43	0.41	
54 Montreal	0.90	0.16	0.033	0.013	0.12	0.08	0.018	0.048	0.006	0.040	0.006	2.31	0.13	
55 Kipawa	1.25	0.19	0.039	0.013	0.14	0.07	0.018	0.048	0.006	0.040	0.006	0.24	0.05	
56 Mattawa	2.50	0.42	0.065	0.038	0.28	0.18	0.036	0.102	0.018	0.086	0.011	0.58	0.08	
57 Dumoine	2.50	0.41	0.059	0.038	0.32	0.18	0.036	0.108	0.012	0.075	0.011	0.38	0.06	
58 Petawawa	3.54	0.62	0.085	0.057	0.49	0.28	0.055	0.157	0.024	0.128	0.017	0.38	0.07	
59 Noire	2.71	0.44	0.059	0.038	0.29	0.17	0.036	0.108	0.018	0.086	0.011	0.91	0.10	
60 Coulonge	2.50	0.37	0.059	0.031	0.24	0.15	0.030	0.090	0.012	0.075	0.011	0.82	0.11	
61 Bonnechere	0.35	0.06	0.013	0.006	0.05	0.04	0.006	0.024	0.006	0.023	0.006	0.87	0.70	
62 Madawaska	0.49	0.09	0.013	0.013	0.08	0.06	0.012	0.048	0.006	0.040	0.006	0.63	0.34	
63 Mississippi	0.14	0.03	0.007	0.006	0.03	0.03	0.006	0.018	0.006	0.017	0.006	0.19	0.87	

Table A5: Trace element analyses for the Ott River and its major tributaries (1992). The shaded bar contains detection limits.

No. River Location	µmole/1000/l														Pb 208	U 238
	Nd 144	Sm 147	Eu 153	Tb 159	Gd 160	Dy 163	Ho 165	Er 166	Tm 169	Yb 174	Lu 175					
64 Rideau	0.14	0.03	0.007	0.006	0.03	0.03	0.006	0.018	0.006	0.023	0.006	1.59	1.99			
65 Gatineau	2.29	0.33	0.046	0.031	0.23	0.13	0.030	0.090	0.012	0.069	0.011	0.43	0.21			
66 Lievre	0.00	0.00	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.00	0.00			
67 Petite Nation	0.90	0.14	0.020	0.013	0.11	0.08	0.018	0.054	0.006	0.040	0.011	0.29	0.19			
68 South Nation	0.56	0.11	0.020	0.013	0.09	0.07	0.018	0.054	0.006	0.057	0.006	0.19	5.66			
69 Rouge	1.81	0.29	0.039	0.038	0.23	0.15	0.036	0.114	0.018	0.096	0.011	0.34	0.10			
70 Ottawa River, Headwaters	2.50	0.41	0.059	0.044	0.27	0.16	0.030	0.102	0.012	0.060	0.011	3.37	0.05			
71 Ottawa River, Lac Dozols	0.56	0.11	0.020	0.013	0.07	0.04	0.012	0.024	0.006	0.011	0.006	1.97	0.02			
72 Ottawa River, Rapide Sept	0.83	0.16	0.026	0.013	0.13	0.07	0.018	0.048	0.006	0.029	0.006	4.38	0.05			
73 Ottawa River, Lac Simard	1.67	0.29	0.052	0.025	0.19	0.12	0.024	0.084	0.012	0.063	0.006	8.22	0.15			
74 Ottawa River, Notre Dame du Nord	1.60	0.23	0.046	0.025	0.23	0.12	0.024	0.060	0.012	0.057	0.006	2.84	0.13			
75 Ottawa River, Temiskaming	1.81	0.28	0.059	0.025	0.22	0.13	0.030	0.078	0.006	0.063	0.011	8.85	0.25			
76 Ottawa River, Mattawa Dam	1.88	0.30	0.059	0.031	0.23	0.13	0.030	0.084	0.012	0.075	0.006	17.40	0.25			
77 Ottawa River, Rolphston	2.15	0.33	0.059	0.031	0.24	0.15	0.030	0.096	0.012	0.069	0.011	6.39	0.23			
78 Ottawa River, Pembroke	0.00	0.00	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.00	0.00			
79 Ottawa River, Portage du Fort	1.94	0.32	0.052	0.031	0.28	0.15	0.030	0.090	0.012	0.069	0.011	15.38	0.21			
80 Ottawa River, Quyon	2.08	0.31	0.052	0.031	0.22	0.15	0.030	0.090	0.012	0.075	0.011	8.75	0.20			
81 Ottawa River, Champlain Bridge	0.00	0.00	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.00	0.00			
82 Ottawa River, Cumberland	0.90	0.14	0.020	0.013	0.11	0.07	0.012	0.054	0.006	0.040	0.006	0.72	0.22			
83 Ottawa River, Montebello	0.90	0.16	0.026	0.019	0.10	0.07	0.018	0.048	0.006	0.040	0.006	2.26	0.21			
84 Ottawa River, Hawkesbury	1.11	0.18	0.026	0.019	0.13	0.09	0.018	0.060	0.006	0.052	0.006	6.01	0.23			
85 Ottawa River, Carillon	1.04	0.17	0.020	0.019	0.13	0.09	0.018	0.060	0.006	0.057	0.006	2.50	0.22			
86 Gatineau	1.18	0.19	0.026	0.013	0.13	0.07	0.018	0.060	0.006	0.046	0.006	1.20	0.16			
87 South Nation	0.49	0.10	0.020	0.013	0.09	0.06	0.012	0.054	0.006	0.046	0.011	9.57	4.71			
88 Rouge	3.06	0.53	0.078	0.063	0.43	0.31	0.067	0.211	0.024	0.172	0.029	1.88	0.10			

Table B1: Average geographic position, area, altitude, and the percentage of land use class per tributary subbasin.

Tributary Basin	Average Latitude	Average Longitude	Area (km ²)	Average Altitude (m)	Mixedwood Forest	Deciduous Forest	Coniferous Forest	Agricultural Cropland	Builtup Areas	Open Water
Camachigama	47.8024	-76.6407	6083	408	70.0	6.2	18.4	0.0	0.0	5.5
Kenojevis	48.0513	-78.6833	8078	311	57.1	7.8	28.8	0.1	0.0	6.3
Blanche	47.9526	-79.8330	5053	282	87.3	0.4	1.4	9.3	0.0	1.7
Montreal	47.6068	-80.4875	6559	363	87.2	1.9	8.4	0.0	0.0	2.6
Kipawa	46.9642	-78.7404	8989	324	62.0	6.5	17.9	5.8	0.0	7.8
Mattawa	46.4825	-79.2261	5827	331	72.9	16.6	8.2	0.0	0.6	1.8
Dumoine	46.7718	-77.8246	4483	366	75.9	14.5	5.9	0.0	0.0	3.7
Petawawa	45.8734	-78.2847	4402	360	83.7	11.3	2.4	0.2	0.0	2.5
Noire	46.3818	-77.2757	2744	306	71.2	24.2	1.0	1.5	0.0	2.1
Coulonge	46.6116	-76.9837	5406	347	78.4	17.6	2.5	0.6	0.0	0.9
Bonnechere	45.5879	-77.2435	4662	219	64.5	14.0	0.7	18.8	0.0	2.1
Madawaska	45.2868	-77.6573	9094	355	67.8	28.3	0.3	0.9	0.0	2.6
Mississippi	45.0432	-76.5323	4632	178	66.6	4.4	0.0	27.1	0.1	1.8
Rideau	44.9038	-75.9966	4232	114	34.6	0.0	0.0	59.3	2.4	3.7
Gatineau	46.9322	-75.9193	24581	337	61.5	24.6	6.1	2.1	0.2	5.6
Lievre	46.6389	-75.2243	10650	353	46.3	44.9	3.0	3.6	0.1	2.1
Petite Nation	46.0244	-75.0576	2717	252	40.8	50.7	0.0	5.8	0.0	2.8
South Nation	45.2682	-75.0972	5697	78	19.8	0.5	0.0	77.0	0.0	0.3
Rouge	46.2378	-74.5430	7977	357	37.8	57.6	0.6	3.6	0.3	0.2

Table B2: Percentage rock type and average soil conditions per tributary basin.

Tributary Basin	Rock Type					Soil Conditions		
	Clastic	Carbonate	Plutonic or Gneissic	Volcanic	Meta-Sedimentary	% Organic Carbon	% Nitrogen	Depth to Water Table
Camachigama	0.0	0.0	100.0	0.0	0.0	30.0	0.21	0.9
Kenojevis	0.0	0.0	66.8	33.2	0.0	6.4	0.08	2.2
Blanche	2.5	4.9	37.2	55.4	0.0	5.2	0.07	2.4
Montreal	0.0	0.0	91.6	8.4	0.0	1.5	0.01	3.5
Kipawa	0.7	0.4	98.9	0.0	0.0	26.5	0.25	1.4
Mattawa	0.0	0.0	100.0	0.0	0.0	1.1	0.01	3.5
Dumoine	0.0	0.0	100.0	0.0	0.0	26.4	0.21	1.3
Petawawa	0.0	0.3	99.7	0.0	0.0	4.7	0.10	2.2
Noire	0.0	0.2	99.8	0.0	0.0	30.8	0.25	0.7
Coulonge	0.0	0.5	99.5	0.0	0.0	8.9	0.25	1.2
Bonnechere	0.0	10.8	49.0	0.0	40.2	1.8	0.01	2.6
Madawaska	0.0	0.9	47.2	0.0	51.9	2.9	0.04	3.2
Mississippi	4.4	19.2	0.0	0.0	76.4	2.9	0.07	3.0
Rideau	11.4	62.3	0.0	0.0	26.3	3.6	0.15	1.9
Gatineau	0.6	0.6	63.2	0.0	23.6	19.6	0.11	1.8
Lievre	0.1	0.4	24.1	0.0	71.3	12.8	0.09	1.7
Petite Nation	0.0	0.2	0.0	0.0	99.7	5.0	0.25	1.5
South Nation	31.0	68.3	0.0	0.0	0.7	2.9	0.09	2.7
Rouge	0.0	3.8	0.2	0.0	42.0	8.9	0.17	1.5

Table B3: Percentage dominant tree species for existing forest per tributary basin.

Tributary Basin	Balsam Fir	Bass- wood	Black Spruce	Eastern Red Spruce	Eastern White Cedar	Eastern White Pine	Hard Maple	Jack Pine	Poplar	Red Maple	Red Oak	Red Pine
Camachachigama	38.4	0.0	11.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kenojevis	46.7	0.0	26.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Blanche	0.7	0.8	9.9	0.0	0.0	0.0	0.0	46.8	21.5	0.0	0.0	0.0
Montreal	0.0	0.0	2.7	0.0	0.0	0.0	0.0	69.4	2.9	0.0	0.0	0.0
Kipawa	9.5	0.0	0.4	0.0	0.4	14.6	0.0	1.7	0.0	0.0	0.0	0.4
Mattawa	0.0	0.0	4.3	0.0	0.0	0.0	2.3	41.6	0.0	0.0	0.0	12.4
Dumoine	9.8	0.0	0.6	0.0	0.0	9.9	0.3	0.0	0.0	0.0	0.0	10.0
Petawawa	0.0	0.0	0.4	0.0	0.0	0.0	56.1	6.5	0.0	0.0	2.0	6.1
Noire	0.9	0.0	0.0	0.7	0.0	2.2	0.0	0.0	0.0	0.0	0.0	12.8
Coulonge	4.0	0.3	0.2	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	16.6
Bonnechere	0.0	0.0	0.0	0.0	0.0	0.4	58.9	0.0	0.0	0.0	0.9	7.1
Madawaska	0.0	0.0	0.1	0.0	0.0	0.0	59.2	0.0	0.0	0.0	14.8	7.4
Mississippi	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	7.0	72.5
Rideau	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	56.2
Gatineau	2.9	0.3	0.5	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	9.8
Lievre	1.2	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.9
Petite Nation	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	14.7
South Nation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.7
Rouge	10.4	0.1	0.2	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	18.7

Tributary Basin	Silver Maple	Sugar Maple	Tamarac	White Elm	White Pine	White Spruce	Yellow Birch	No Unclass- Domin. Species	% Con- ified	% Con- iferous	% Dec- iduous
Camachachigama	0.0	15.9	0.0	0.0	0.0	0.0	22.5	0.0	12.0	56.3	43.7
Kenojevis	0.0	0.3	0.0	0.0	0.0	0.0	26.5	0.4	0.0	73.1	26.9
Blanche	0.0	0.0	0.0	0.3	0.6	0.0	14.6	4.8	0.1	61.0	39.0
Montreal	0.0	0.0	0.0	0.0	23.8	0.0	0.0	1.2	0.0	97.1	2.9
Kipawa	0.0	28.6	0.0	4.1	0.3	0.2	39.8	0.0	0.0	27.4	72.6
Mattawa	0.0	0.0	0.0	0.0	35.4	3.7	0.0	0.2	0.0	97.6	2.4
Dumoine	0.0	12.8	0.0	0.0	0.2	15.1	41.5	0.0	0.0	35.8	64.2
Petawawa	0.0	0.0	0.0	0.0	27.8	1.1	0.0	0.0	0.0	41.9	58.1
Noire	0.0	34.6	0.0	0.0	0.2	0.0	46.8	0.0	0.0	17.0	83.0
Coulonge	0.0	27.6	0.0	0.3	0.1	0.0	49.0	0.0	0.0	22.9	77.1
Bonnechere	0.0	0.0	0.0	0.0	32.3	0.4	0.0	0.0	0.0	40.2	59.8
Madawaska	0.0	0.0	0.0	0.0	16.2	1.6	0.6	0.2	0.0	25.2	74.8
Mississippi	0.0	0.0	0.0	0.0	0.6	14.1	0.0	3.6	0.0	90.4	9.6
Rideau	0.0	0.0	3.9	0.0	0.0	35.7	0.0	1.8	0.0	93.6	6.4
Gatineau	0.0	21.1	0.0	1.9	0.0	0.0	25.5	0.2	35.3	24.4	75.6
Lievre	0.1	17.5	0.0	4.5	0.0	0.1	28.2	0.0	34.8	22.6	77.4
Petite Nation	0.1	53.6	0.0	5.4	0.0	0.0	26.1	0.0	0.0	14.9	85.1
South Nation	0.0	1.8	3.3	3.2	0.4	62.5	0.0	0.1	0.0	91.7	8.3
Rouge	0.0	23.6	0.0	1.9	0.0	0.0	42.2	0.0	2.6	30.4	69.6

Appendix C

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	StdDev	Cnt	Max	Min	Avg	First Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Noire Dame	On02Je0004	Al ex.	mg/l	0.036	0.19	15	0.88	0.13	0.33	1982 1985	5.70	6.47	7.22	6.05	0.37	6.60	6.92	0.29	0.42	0.42	0.40	
Noire Dame	On02Je0004	Alk tot.	mg/l	5.07	2.25	106	22	3.00	6.48	1978 1988	1.38	1.36	2.22	1.82	1.87	2.31	1.49	1.47	6.61	5.91	6.36	6.00
Noire Dame	On02Je0004	C ds.	mg/l	0.68	0.83	83	6.80	0.60	1.60	1984 1988	6.79	5.22	4.75	6.15	6.66	7.01	6.99	6.74	6.74	6.39	6.70	6.71
Noire Dame	On02Je0004	C ds.	mg/l	1.78	1.33	86	8.80	0.20	6.40	1984 1988	13	19	12	13	12	14	12	17	11	11	11	15
Noire Dame	On02Je0004	C tot.	mg/l	54	7.35	143	77	5.50	13	1978 1983	1.95	4.27	2.17	1.75	1.44	1.39	1.50	2.71	1.25	1.39	1.42	1.71
Noire Dame	On02Je0004	C tot. inorg.	mg/l	5.05	2.25	143	22	0.50	1.96	1978 1983	4.22	3.77	3.92	3.62	4.43	4.47	4.12	3.63	3.82	3.44	3.70	3.60
Noire Dame	On02Je0004	Ca tot.	mg/l	1.12	1.06	132	12	2.70	3.88	1979 1988												
Noire Dame	On02Je0004	Chloro A	mg/m			1	0.44	0.44	0.44	1980 1980		0.44										
Noire Dame	On02Je0004	Cl ds.	mg/l	0.080	0.28	139	2.00	0.50	1.03	1979 1988	0.97	1.04	1.09	1.07	1.13	1.19	1.02	0.87	0.93	0.93	1.04	1.12
Noire Dame	On02Je0004	Cond.	usie/c	38	6.18	217	75	18	39	1978 1988	37	35	40	39	44	45	42	39	38	35	37	38
Noire Dame	On02Je0004	Fe ex.	mg/l	0.023	0.15	77	0.74	0.090	0.36	1979 1983	0.30	0.40	0.19	0.43	0.31	0.32	0.34	0.31	0.39	0.41	0.53	0.38
Noire Dame	On02Je0004	Fe tot.	mg/l	0.013	0.12	62	0.68	0.10	0.31	1984 1988	0.31	0.29	0.33	0.37	0.37	0.28	0.36	0.17	0.22	0.26	0.36	0.34
Noire Dame	On02Je0004	HCO3 calc.	mg/l	3.88	1.97	15	13	5.10	7.29	1986 1987	6.15	5.80	5.90	7.40	13	8.60	7.60	6.20	6.70	6.70	7.00	7.05
Noire Dame	On02Je0004	Hg tot.	ug/l	0.000	0.000	8	0.050	0.050	0.050	1980 1981		0.050						0.050		0.050		
Noire Dame	On02Je0004	K ds.	mg/l			1	0.70	0.70	0.70	1979 1979								0.70				
Noire Dame	On02Je0004	Mg tot.	mg/l	0.11	0.34	68	2.80	0.80	1.28	1979 1983	1.40	1.15	1.55	1.44	1.44	1.50	1.35	1.17	1.16	1.17	1.20	1.12
Noire Dame	On02Je0004	Mn ex.	mg/l	0.000	0.013	80	0.10	0.010	0.022	1979 1984	0.018	0.019	0.022	0.017	0.030	0.012	0.018	0.022	0.037	0.023	0.023	0.020
Noire Dame	On02Je0004	Mn tot.	mg/l	0.000	0.008	62	0.050	0.010	0.021	1984 1988	0.018	0.019	0.017	0.020	0.034	0.022	0.024	0.018	0.023	0.017	0.020	0.020
Noire Dame	On02Je0004	N ds.	mg/l	0.010	0.10	52	0.74	0.26	0.38	1985 1988	0.34	0.37	0.32	0.37	0.48	0.47	0.44	0.31	0.34	0.29	0.34	0.42
Noire Dame	On02Je0004	N ds.	mg/l	0.005	0.069	76	0.49	0.10	0.21	1980 1983	0.23	0.20	0.16	0.20	0.18	0.21	0.25	0.24	0.17	0.19	0.21	0.25
Noire Dame	On02Je0004	N tot. kjeld.	mg/l	0.008	0.079	102	0.59	0.10	0.23	1978 1985	0.25	0.25	0.23	0.23	0.26	0.24	0.24	0.22	0.22	0.19	0.20	0.20
Noire Dame	On02Je0004	Na ds.	mg/l			1	1.30	1.30	1.30	1979 1979								1.30				
Noire Dame	On02Je0004	NH4 ds.	mg/l	0.001	0.026	80	0.22	0.010	0.032	1979 1983	0.025	0.031	0.035	0.034	0.033	0.030	0.037	0.046	0.027	0.025	0.026	0.022
Noire Dame	On02Je0004	NH4 tot.	mg/l	0.001	0.029	151	0.25	0.001	0.035	1978 1988	0.042	0.041	0.040	0.025	0.031	0.035	0.039	0.027	0.028	0.030	0.048	0.028
Noire Dame	On02Je0004	NO2 + NO3 ds.	mg/l	0.001	0.037	230	0.26	0.060	0.12	1978 1988	0.12	0.12	0.15	0.18	0.19	0.14	0.11	0.097	0.091	0.094	0.11	0.12
Noire Dame	On02Kf0011	O2 ds.	mg/l	3.24	1.80	22	15	9.40	12	1979 1985		14		14	14			9.90		12		
Noire Dame	On02Kf0011	P susp.	ug/l	0.000	0.012	196	0.093	0.000	0.009	1980 1988	0.008	0.011	0.011	0.009	0.011	0.010	0.007	0.011	0.007	0.009	0.010	0.007
Noire Dame	On02Kf0011	P tot.	mg/l	0.001	0.027	17	0.095	0.000	0.027	1978 1987	0.055	0.015	0.012	0.043	0.061	0.028	0.076	0.000		0.014	0.016	0.012
Noire Dame	On02Kf0011	P tot. ds.	mg/l	0.000	0.018	176	0.22	0.006	0.015	1979 1985	0.020	0.015	0.013	0.016	0.014	0.015	0.017	0.021	0.014	0.012	0.012	0.010
Noire Dame	On02Kf0011	pH	ph	0.066	0.26	158	7.50	5.50	6.74	1979 1988	6.58	6.61	6.60	6.68	6.79	6.75	6.87	6.88	6.75	6.78	6.77	6.76
Noire Dame	On02Kf0011	PO4 ds.	mg/l	0.000	0.010	52	0.070	0.010	0.013	1985 1988	0.010	0.030	0.010	0.010	0.012	0.021	0.011	0.010	0.013	0.010	0.011	0.010
Noire Dame	On02Kf0011	Si reacl.	mg/l	1.48	1.22	80	8.60	1.30	3.84	1979 1985	3.12	3.99	3.98	4.98	5.25	4.17	3.67	3.13	3.23	3.32	3.68	3.47
Noire Dame	On02Kf0011	SO4 ds.	mg/l	0.94	0.97	136	10	4.50	7.60	1979 1988	7.25	7.35	7.28	7.12	8.13	8.50	7.83	7.34	7.60	7.71	7.24	7.71
Noire Dame	On02Kf0011	Sr. tot.	mg/l	0.000	0.005	4	0.030	0.020	0.027	1982 1983		0.030			0.020			0.030				
Noire Dame	On02Kf0011	Temp	deg C	58	7.62	255	28	0.000	9.10	1978 1988	1.14	1.28	2.25	3.31	7.84	15	21	20	16	9.78	5.48	1.94
Temiscaming	On02Kf0011	Al ex.	mg/l	0.007	0.082	15	0.35	0.090	0.20	1982 1985		0.28			0.22			0.15		0.15	0.15	0.19

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	SD	CV	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temiscaming	On02K00011	Alk tot.	mg/l	8.23	2.87	114	22	6.00	16	1978	1988	17	15	15	12	13	17	18	19	18	17	17	18
Temiscaming	On02K00011	C dis.	mg/l	0.33	0.58	82	5.40	2.80	4.15	1984	1988	4.38	3.96	3.35	3.12	3.52	4.12	4.41	4.50	4.60	4.56	4.57	4.47
Temiscaming	On02K00011	C dis.	mg/l	0.66	0.81	84	8.10	0.80	5.84	1984	1988	5.86	5.33	5.84	6.05	5.73	5.60	5.86	6.34	6.30	5.84	5.78	5.72
Temiscaming	On02K00011	C tot.	mg/l	10	3.16	184	30	7.00	14	1978	1983	14	13	13	13	12	13	15	14	14	14	14	14
Temiscaming	On02K00011	C tot. inorg.	mg/l	3.48	1.86	184	24	0.50	3.77	1978	1983	3.78	3.72	3.43	2.64	2.97	3.38	4.00	5.13	4.35	3.87	4.06	4.10
Temiscaming	On02K00011	Ca dis.	mg/l			1	6.00	6.00	6.00	1979	1979		6.00										
Temiscaming	On02K00011	Ca tot.	mg/l	1.06	1.03	150	12	4.20	6.95	1979	1988	7.00	7.06	7.12	5.68	6.17	7.12	7.27	7.65	7.63	6.94	7.02	7.27
Temiscaming	On02K00011	Chloro A	mg/m			1	0.28	0.28	0.28	1980	1980		0.28										
Temiscaming	On02Lb0002	Cl dis.	mg/l	0.70	0.84	156	10	0.40	1.34	1979	1988	1.37	1.85	1.31	1.32	1.20	1.26	1.24	1.20	1.26	1.24	1.46	1.33
Temiscaming	On02Lb0002	Cond.	usie/c	119	11	239	163	34	62	1978	1988	64	61	59	53	60	62	65	65	65	62	64	63
Temiscaming	On02Lb0002	Fe ex.	mg/l	0.015	0.12	78	0.72	0.070	0.21	1980	1983	0.27	0.33	0.33	0.31	0.19	0.21	0.14	0.12	0.14	0.17	0.19	0.20
Temiscaming	On02Lb0002	Fe tot.	mg/l	0.006	0.080	75	0.39	0.060	0.21	1979	1988	0.24	0.25	0.21	0.26	0.21	0.20	0.21	0.17	0.13	0.16	0.19	0.24
Temiscaming	On02Lb0002	HCO3 calc.	mg/l	4.55	2.13	13	23	16	21	1986	1987	22	21	18	16	18	22	22	0.050	21	22	23	23
Temiscaming	On02Lb0002	Hg ex.	ug/l	0.000	0.000	4	0.050	0.050	0.050	1979	1979		0.050			0.050		0.050	0.050		0.050		
Temiscaming	On02Lb0002	Hg tot.	ug/l	0.005	0.072	7	0.24	0.050	0.077	1980	1981		0.050	0.050				0.24	0.24		0.050		
Temiscaming	On02Lb0002	K dis.	mg/l			1	0.80	0.80	0.80	1979	1979		0.050					0.80	0.80				
Temiscaming	On02Lb0002	Mg dis.	mg/l			1	1.60	1.60	1.60	1979	1979		1.60										
Temiscaming	On02Lb0002	Mg tot.	mg/l	0.078	0.28	81	2.90	1.30	1.91	1979	1983	1.92	1.74	1.72	1.91	1.93	1.96	2.06	1.97	1.96	1.82	2.05	1.88
Temiscaming	On02Lb0002	Mn ex.	mg/l	0.000	0.017	82	0.16	0.010	0.014	1980	1984	0.010	0.029	0.012	0.013	0.011	0.010	0.013	0.012	0.013	0.012	0.013	0.014
Temiscaming	On02Lb0002	Mn tot.	mg/l	0.000	0.002	75	0.020	0.010	0.010	1979	1988	0.010	0.010	0.010	0.013	0.011	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Temiscaming	On02Lb0002	N dis.	mg/l	0.004	0.060	49	0.55	0.27	0.38	1985	1988	0.40	0.34	0.41	0.39	0.41	0.34	0.36	0.38	0.37	0.36	0.36	0.42
Temiscaming	On02Lb0002	N dis.	mg/l	0.003	0.056	89	0.47	0.020	0.18	1979	1983	0.18	0.20	0.16	0.16	0.16	0.15	0.23	0.20	0.18	0.17	0.15	0.17
Temiscaming	On02Lb0002	N tot. kield.	mg/l	0.003	0.051	111	0.46	0.11	0.19	1978	1985	0.18	0.19	0.18	0.17	0.18	0.19	0.21	0.22	0.19	0.18	0.22	0.15
Temiscaming	On02Lb0002	Na dis.	mg/l			1	1.60	1.60	1.60	1979	1979								1.60				
Temiscaming	On02Lb0002	NH4 dis.	mg/l	0.000	0.015	89	0.12	0.010	0.025	1979	1983	0.022	0.019	0.020	0.027	0.024	0.021	0.038	0.031	0.023	0.024	0.020	0.020
Temiscaming	On02Lb0002	NH4 tot.	mg/l	0.000	0.017	161	0.14	0.001	0.023	1978	1988	0.023	0.024	0.022	0.020	0.024	0.022	0.032	0.034	0.017	0.023	0.022	0.018
Temiscaming	On02Lb0002	NO2 + NO3 dis.	mg/l	0.001	0.025	249	0.27	0.10	0.17	1978	1988	0.18	0.17	0.17	0.17	0.18	0.16	0.15	0.15	0.16	0.17	0.19	0.20
Temiscaming	On02Lb0002	O2 dis.	mg/l	4.31	2.08	23	14	8.60	11	1979	1985		13		14	13			8.80		11		
Temiscaming	Pq02Lc0001	P susp.	ug/l	0.000	0.008	210	0.049	0.000	0.006	1980	1988	0.007	0.008	0.008	0.009	0.007	0.007	0.004	0.005	0.005	0.006	0.007	0.004
Temiscaming	Pq02Lc0001	P tot.	mg/l	0.000	0.011	15	0.037	0.006	0.019	1978	1987	0.018	0.018	0.011	0.037	0.029	0.037		0.005	0.022	0.011	0.023	0.008
Temiscaming	Pq02Lc0001	P tot. dis.	mg/l	0.000	0.012	173	0.14	0.006	0.012	1980	1985	0.023	0.017	0.012	0.014	0.011	0.012	0.014	0.009	0.010	0.009	0.010	0.010
Temiscaming	Pq02Lc0001	pH	ph	0.082	0.29	156	8.00	6.40	7.16	1979	1988	7.20	7.11	7.04	7.01	6.98	7.24	7.26	7.39	7.27	7.13	7.18	7.10
Temiscaming	Pq02Lc0001	PO4 dis.	mg/l	0.000	0.004	49	0.030	0.010	0.012	1985	1988	0.012	0.010	0.010	0.011	0.012	0.010	0.014	0.012	0.014	0.010	0.011	0.010
Temiscaming	Pq02Lc0001	Si react.	mg/l	0.47	0.69	100	7.50	1.40	4.08	1979	1985	4.06	4.21	3.84	4.16	4.48	3.99	4.12	3.85	3.82	3.90	4.10	4.10
Temiscaming	Pq02Lc0001	SO4 dis.	mg/l	1.78	1.33	153	19	6.50	8.74	1979	1988	8.43	9.62	9.63	8.60	8.53	8.38	8.32	8.28	8.48	9.15	8.38	8.74
Temiscaming	Pq02Lc0001	Sr. tot.	mg/l	0.000	0.005	4	0.040	0.030	0.037	1982	1983		0.030			0.040			0.040				

Appendix C

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	StDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temiscaming	Pq02Jc0001	Temp	deg C	48	6.94	278	21	1.00	8.21	1978	1988	1.10	1.14	1.09	1.79	4.36	10	18	19	17	12	7.14	4.00
Otto Holden	Pq02Jc0001	Alk tot. CaCO ₃	mg/l	13	3.57	55	24	2.00	17	1971	1984	10	14	15	15	14	16	17	19	20	19	20	18
Otto Holden	Pq02Jc0001	BOD	mg/l	0.90	0.95	85	7.50	0.20	1.39	1971	1979	1.37	2.21	1.67	1.88	1.06	1.53	1.09	1.26	0.83	1.01	1.50	1.20
Otto Holden	Pq02Jc0001	C tot. inorg.	mg/l	0.68	0.82	5	4.50	3.00	3.60	1973	1973	4.50	4.50	3.00									
Otto Holden	Pq02Jc0001	Ca dis.	mg/l	0.23	0.48	8	9.90	8.50	9.09	1973	1973	9.30	9.30	8.60			9.43						
Otto Holden	Pq02Jc0001	Cl dis.	mg/l	0.26	0.51	115	4.00	0.90	1.65	1971	1984	1.66	1.67	1.85	1.70	1.63	1.40	1.48	1.95	1.72	1.61	1.59	1.65
Otto Holden	Pq02Jc0001	Cond.	usiel/c	64	8.02	158	102	40	66	1971	1984	68	64	60	60	58	64	67	72	69	70	69	68
Otto Holden	Pq02Jc0001	Daily mean	m3/s	165044	406	114	2420	65	705	1971	1981	593	728	677	1099	1258	641	548	420	415	581	616	804
Otto Holden	Pq02Jc0001	Fe tot.	mg/l	0.017	0.13	40	0.87	0.15	0.34	1971	1984	0.48		0.87	0.38	0.32	0.38	0.31	0.21	0.25	0.27	0.33	0.36
Otto Holden	Pq02Jc0001	Hg tot.	ug/l	3.98	2.00	4	4.00	0.010	1.01	1971	1984	4.00						0.70			0.010	0.010	0.010
Otto Holden	Pq02Jc0001	K dis.	mg/l	0.002	0.046	8	0.80	0.70	0.72	1973	1973		0.80	0.70									
Otto Holden	Pq02Jc0001	Mg tot.	mg/l	0.088	0.30	2	1.94	1.52	1.73	1984	1984							0.70					
Otto Holden	Pq02Jc0001	Mn tot.	mg/l	0.000	0.001	2	0.019	0.018	0.018	1984	1984										1.94	1.52	
Otto Holden	Pq02Jc0001	N tot.	mg/l	0.055	0.23	130	2.29	0.32	0.70	1971	1984	0.58	0.66	0.68	0.65	0.53	0.68	0.79	0.83	0.73	0.78	0.76	0.64
Otto Holden	Pq02Jc0001	N tot. liqld.	mg/l	0.052	0.23	242	2.18	0.050	0.46	1971	1984	0.34	0.39	0.45	0.44	0.34	0.46	0.62	0.57	0.45	0.50	0.47	0.38
Otto Holden	Pq02Jc0001	Na dis.	mg/l	0.026	0.16	8	1.70	1.20	1.44	1973	1973		1.55	1.40			1.40						
Otto Holden	Pq02Jc0001	NH4 dis.	mg/l	0.014	0.12	116	0.55	0.010	0.19	1971	1984	0.15	0.17	0.15	0.17	0.11	0.16	0.17	0.34	0.20	0.26	0.22	0.17
Otto Holden	Pq02Jc0001	NO2 + NO3 dis.	mg/l	0.000	0.021	7	0.13	0.070	0.11	1973	1973		0.10	0.13				0.083					
Otto Holden	Pq02Jc0001	NO3 dis.	mg/l	0.003	0.052	132	0.48	0.030	0.15	1971	1984	0.15	0.18	0.17	0.15	0.14	0.15	0.13	0.14	0.17	0.15	0.17	0.17
Otto Holden	Pq02Jc0001	NO3 dis.	mg/l	0.000	0.002	107	0.010	0.002	0.005	1971	1984	0.006	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.005	0.006	0.004	0.005
Otto Holden	Pq02Jc0001	O2 dis.	mg/l	5.85	2.42	115	13	3.40	8.24	1971	1984	9.88	11	10	10	9.45	8.72	8.08	6.14	6.27	7.18	7.02	8.20
Otto Holden	Pq02Jc0001	P tot.	mg/l	0.000	0.021	144	0.21	0.004	0.019	1971	1984	0.015	0.021	0.023	0.016	0.014	0.016	0.021	0.024	0.016	0.018	0.031	0.015
Otto Holden	Pq02Jc0001	pH	ph	0.071	0.27	72	7.75	6.33	7.05	1971	1984	7.20	7.02	6.78	7.02	7.09	7.09	7.23	7.11	7.03	6.82	7.06	7.43
Otto Holden	Pq02Jc0001	PO4 dis.	mg/l	0.000	0.004	104	0.022	0.001	0.004	1971	1981	0.007	0.006	0.006	0.003	0.004	0.005	0.003	0.003	0.004	0.003	0.004	0.004
Otto Holden	Pq02Jc0001	SO4 dis.	mg/l	0.13	0.35	8	11	10	11	1973	1973		11	11				11					
Otto Holden	Pq02Jc0001	Temp	deg C	60	7.74	156	25	0.000	10	1971	1984	1.21	4.36	4.87	3.29	7.33	14	20	20	17	9.95	6.34	1.25
Chenaux	Pq02Jc0001	Al ex.	mg/l	0.003	0.058	15	0.25	0.080	0.15	1982	1985		0.20			0.20		0.10	0.10		0.12	0.10	
Chenaux	Pq02Jc0003	Alk tot. CaCO ₃	mg/l	10	3.19	116	36	7.00	14	1978	1988	16	16	16	14	13	12	13	14	13	13	13	14
Chenaux	Pq02Jc0003	C dis.	mg/l	1.20	1.10	85	11	2.00	3.59	1984	1988	3.77	4.34	4.50	4.28	2.69	2.46	4.05	3.34	3.48	3.55	3.52	3.50
Chenaux	Pq02Jc0003	C dis.	mg/l	0.38	0.62	87	7.60	3.20	6.12	1984	1988	6.24	6.13	6.10	6.07	5.87	5.80	5.63	6.10	6.17	6.36	6.45	6.70
Chenaux	Pq02Jc0003	C tot.	mg/l	20	4.51	162	36	6.00	15	1978	1983	17	16	16	14	14	14	15	15	15	14	18	14
Chenaux	Pq02Jc0003	C tot. inorg.	mg/l	3.43	1.85	162	23	0.50	3.29	1978	1983	4.11	3.78	4.12	3.00	2.41	2.25	2.73	4.26	3.41	2.97	3.29	3.33
Chenaux	Pq02Jc0003	Ca dis.	mg/l			1	6.50	6.50	6.50	1979	1979		6.50										
Chenaux	Pq02Jc0003	Ca tot.	mg/l	0.66	0.81	150	9.80	4.60	6.34	1979	1988	6.53	7.05	7.07	6.45	5.45	5.53	5.92	6.35	6.26	6.41	6.69	6.91
Chenaux	Pq02Jc0003	Chloro A	mg/m			1	0.28	0.28	0.28	1980	1980		0.28										
Chenaux	Pq02Jc0003	Cl dis.	mg/l	0.27	0.52	158	4.80	1.00	1.93	1979	1988	1.86	1.94	1.69	1.81	1.50	1.62	2.00	2.23	2.24	2.08	2.18	2.10

Appendix C

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	StDev	Cnt	Max	Min	Avg	Firct	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chenaux	Pq02Je0003	Cond.	usie/c	44	6.60	238	77	37	60	1978	1988	64	63	66	60	53	52	57	62	62	60	64	63
Chenaux	Pq02Je0003	Fe ex.	mg/l	0.005	0.074	76	0.46	0.050	0.23	1980	1983	0.25	0.26	0.26	0.31	0.20	0.19	0.18	0.19	0.26	0.24	0.22	0.28
Chenaux	Pq02Je0003	Fe tot.	mg/l	0.086	0.29	78	2.22	0.11	0.30	1979	1988	0.23	0.23	0.54	0.55	0.26	0.23	0.49	0.16	0.19	0.22	0.26	0.40
Chenaux	Pq02Je0003	HCO3 calc.	mg/l	6.66	2.58	15	22	13	18	1986	1987	20	20	22	18	13	14	17	18	17	18	18	20
Chenaux	Pq02Je0003	Hg ex.	ug/l	0.000	0.000	4	0.050	0.050	0.050	1979	1979		0.050			0.050			0.050		0.050		
Chenaux	Pq02Je0003	Hg tot.	ug/l	0.000	0.000	8	0.050	0.050	0.050	1980	1981		0.050		0.050				0.050		0.050		
Chenaux	Pq02Je0003	K ds.	mg/l			1	0.80	0.80	0.80	1979	1979								0.80				
Chenaux	Pq02Je0003	Mg ds.	mg/l			1	1.70	1.70	1.70	1979	1979		1.70										
Chenaux	Pq02Je0003	Mg tot.	mg/l	0.051	0.23	81	2.40	1.20	1.75	1979	1983	1.78	1.78	1.86	1.98	1.56	1.63	1.82	1.74	1.70	1.61	1.82	1.86
Chenaux	Pq02Je0003	Mn ex.	mg/l	0.000	0.008	80	0.040	0.010	0.017	1980	1984	0.010	0.012	0.012	0.017	0.014	0.012	0.017	0.025	0.022	0.017	0.020	0.024
Chenaux	Pq02Je0003	Mn tot.	mg/l	0.000	0.010	78	0.060	0.010	0.020	1979	1988	0.015	0.016	0.022	0.028	0.019	0.020	0.021	0.021	0.022	0.021	0.014	0.026
Chenaux	Pq02Je0003	N ds.	mg/l	0.012	0.11	51	0.73	0.26	0.43	1985	1988	0.50	0.52	0.48	0.50	0.39	0.34	0.32	0.40	0.41	0.44	0.50	0.53
Chenaux	Pq02Je0003	N ds.	mg/l	0.014	0.12	86	1.12	0.060	0.24	1979	1983	0.25	0.27	0.23	0.28	0.22	0.20	0.25	0.30	0.23	0.21	0.19	0.26
Chenaux	Pq02Je0003	N tot. Yield.	mg/l	0.003	0.059	113	0.42	0.14	0.25	1978	1985	0.28	0.27	0.28	0.31	0.25	0.23	0.22	0.22	0.21	0.23	0.23	0.27
Chenaux	Pq02Je0003	Na ds.	mg/l			1	2.30	2.30	2.30	1979	1979								2.30				
Chenaux	Pq02Je0003	NH4 ds.	mg/l	0.001	0.036	86	0.16	0.010	0.053	1979	1983	0.088	0.11	0.083	0.085	0.047	0.043	0.034	0.037	0.038	0.027	0.023	0.045
Chenaux	Pq02Je0003	NH4 tot.	mg/l	0.002	0.046	166	0.20	0.003	0.057	1978	1988	0.097	0.092	0.092	0.077	0.048	0.038	0.037	0.032	0.023	0.022	0.042	0.071
Chenaux	Pq02Je0003	NO2 + NO3 ds.	mg/l	0.005	0.069	251	0.70	0.060	0.21	1978	1988	0.21	0.21	0.21	0.21	0.15	0.15	0.15	0.20	0.24	0.26	0.29	0.25
Chenaux	Pq02Je0003	O2 ds.	mg/l	4.40	2.10	23	15	8.00	11	1979	1985		13		14	13			8.47		11		
Chenaux	Pq02Je0003	P susp.	ug/l	0.000	0.009	208	0.048	0.000	0.008	1980	1988	0.009	0.009	0.010	0.012	0.009	0.009	0.006	0.007	0.009	0.007	0.007	0.005
Chenaux	Pq02Je0003	P tot.	mg/l	0.021	0.14	17	0.61	0.006	0.060	1978	1987	0.071	0.31	0.015	0.049	0.032	0.028	0.016	0.012	0.012	0.018	0.015	0.008
Chenaux	Pq02Je0003	P tot. ds.	mg/l	0.000	0.009	170	0.070	0.006	0.013	1980	1985	0.014	0.015	0.015	0.014	0.010	0.011	0.019	0.011	0.012	0.013	0.012	0.017
Chenaux	Pq02Je0003	pH	ph	0.070	0.26	156	8.20	5.60	7.06	1979	1988	7.14	6.98	7.06	7.03	6.98	6.98	7.05	7.13	7.14	7.12	7.08	7.09
Chenaux	Pq02Je0003	PO4 ds.	mg/l	0.007	0.081	52	0.60	0.010	0.022	1985	1988	0.010	0.21	0.010	0.011	0.010	0.015	0.012	0.010	0.010	0.010	0.010	0.010
Chenaux	Pq02Je0003	Si react.	mg/l	0.83	0.91	99	8.30	1.40	4.20	1979	1985	4.38	4.76	4.29	3.85	4.95	3.91	4.01	3.57	3.43	3.82	4.06	4.52
Chenaux	Pq02Je0003	SO4 ds.	mg/l	1.53	1.24	155	13	6.50	9.00	1979	1988	9.50	9.93	9.29	9.31	8.42	8.26	8.29	8.49	8.79	9.21	9.14	9.60
Chenaux	Pq02Je0003	Sr. tot.	mg/l	0.000	0.010	4	0.050	0.030	0.035	1982	1983		0.030			0.030			0.040				
Chenaux	Pq02Je0003	Temp	deg C	55	7.40	274	23	0.000	8.77	1978	1988	0.41	0.35	0.21	2.70	7.90	14	18	20	17	11	6.10	2.40
Chats Falls	Pq02Je0003	Alk tot. CaCO3	mg/l	71	8.44	43	48	5.00	29	1971	1984	30	35	38		34	26	21	21	19	26	36	31
Chats Falls	Pq02Kc0002	BOD	mg/l	0.75	0.87	55	5.00	0.20	1.23	1971	1979	2.05	0.70	0.86	1.00	1.74	1.20	0.88	0.58	1.20	1.57	1.10	1.10
Chats Falls	Pq02Kc0002	Cl ds.	mg/l	2.37	1.54	61	9.50	1.50	3.34	1971	1984	3.67	3.75	3.92	6.75	2.64	2.11	2.21	3.67	2.76	3.60	3.92	3.76
Chats Falls	Pq02Kc0002	Cond.	usie/c	6768	82	100	590	65	115	1971	1984	102	102	179	123	105	102	86	94	89	88	154	97
Chats Falls	Pq02Kc0002	Daily mean	m3/s	646924	804	115	5410	425	1265	1971	1981	1051	1030	1303	2254	2752	1340	999	770	590	886	1053	1068
Chats Falls	Pq02Kc0002	Fe tot.	mg/l	0.006	0.077	42	0.45	0.13	0.24	1971	1984	0.33	0.21	0.28		0.25	0.24	0.20	0.17	0.17	0.21	0.26	0.23
Chats Falls	Pq02Kc0002	Hg tot.	ug/l	0.000	0.000	5	0.010	0.010	0.010	1984	1984		0.010	0.010		0.010	0.010	0.010	0.17	0.010		0.26	0.23
Chats Falls	Pq02Kc0002	Mg tot.	mg/l	0.41	0.64	5	3.36	1.80	2.44	1984	1984		3.36			2.84		1.80		2.06			2.16

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	SD	Dev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chats Falls	Pq02Kc0002	Mn tot.	mg/l	0.000	0.004	0.004	6	0.025	0.015	0.019	1984	1984			0.018		0.020	0.023	0.025	0.016				
Chats Falls	Pq02Kc0002	N tot.	mg/l	0.13	0.36	0.36	65	2.32	0.18	0.61	1971	1984	0.62	0.48	0.97	0.69	0.61	0.49	0.43	0.42	0.47	0.58	0.60	0.55
Chats Falls	Pq02Kc0002	N tot. kjeld.	mg/l	0.031	0.17	0.17	144	1.12	0.010	0.38	1971	1984	0.44	0.31	0.43	0.42	0.44	0.34	0.32	0.32	0.33	0.36	0.35	0.32
Chats Falls	Pq02Kc0002	NH4 dis.	mg/l	0.003	0.051	0.051	74	0.37	0.002	0.054	1971	1984	0.074	0.056	0.10	0.060	0.046	0.044	0.044	0.034	0.030	0.063	0.025	0.057
Chats Falls	Pq02Kc0002	NO3 dis.	mg/l	0.067	0.26	0.26	69	1.94	0.010	0.19	1971	1984	0.14	0.13	0.48	0.23	0.14	0.13	0.086	0.072	0.12	0.16	0.23	0.20
Chats Falls	Pq02Kc0002	NO3 dis.	mg/l	0.000	0.008	0.008	70	0.068	0.002	0.007	1971	1984	0.006	0.009	0.008	0.007	0.013	0.005	0.004	0.004	0.005	0.005	0.005	0.007
Chats Falls	Pq02Kc0002	O2 dis.	mg/l	5.80	2.41	2.41	141	15	2.00	10	1971	1984	10	12	11	11	11	9.75	8.54	8.42	8.54	8.46	11	11
Chats Falls	Pq02Kc0002	P tot.	mg/l	0.001	0.028	0.028	102	0.26	0.004	0.025	1971	1984	0.030	0.023	0.025	0.032	0.025	0.019	0.050	0.021	0.020	0.022	0.023	0.018
Chats Falls	Pq02Kc0002	pH	ph	0.056	0.24	0.24	42	8.20	7.05	7.55	1971	1984	7.39	7.69	7.48		7.53	7.46	7.36	7.53	7.73	7.62	7.67	7.83
Chats Falls	Pq02Kc0002	PO4 dis.	mg/l	0.001	0.024	0.024	66	0.19	0.001	0.010	1971	1980	0.007	0.006	0.012	0.016	0.005	0.005	0.036	0.006	0.004	0.008	0.009	0.004
Chats Falls	Pq02Kc0002	Temp	deg C	85	9.21	142	142	27	0.000	10	1971	1984	0.20	0.14	0.84	2.64	12	20	22	23	19	9.67	5.05	0.65
Masson	Pq02Kc0002	Al ex.	mg/l	0.009	0.096	0.096	15	0.40	0.050	0.17	1982	1985		0.17	0.33	0.33	0.15		0.11	0.050	0.12	0.16		
Masson	Pq02Kc0002	Alk tot. CaCO3	mg/l	49	6.97	97	46	9.00	22	1980	1988	20	22	23	28	25	25	21	17	18	20	23	20	35
Masson	Pq02Kc0002	C dis.	mg/l	3.42	1.85	85	11	0.40	5.59	1984	1988	5.55	6.15	7.86	8.96	5.41	4.99	4.44	4.38	4.83	4.29	5.06	6.13	6.13
Masson	Pq02Kc0002	C dis.	mg/l	0.36	0.60	87	8.20	4.30	5.89	1984	1988	5.98	5.89	5.80	5.63	6.13	6.13	5.79	5.69	5.60	6.13	5.99	5.94	6.27
Masson	Pq02Kc0002	C tot.	mg/l	14	3.68	125	30	9.50	16	1980	1983	18	17	16	16	17	17	15	15	15	16	16	17	17
Masson	Pq02Kc0002	C tot. inorg.	mg/l	3.29	1.61	125	11	0.50	5.44	1980	1983	5.93	5.54	6.44	6.05	5.73	4.25	4.25	3.50	4.35	5.88	4.73	6.11	7.28
Masson	Pq02Kc0002	Ca tot.	mg/l	4.85	2.20	124	16	1.60	8.89	1980	1988	8.81	8.82	10	11	9.48	8.18	8.18	7.63	7.41	8.03	7.86	9.10	11
Masson	Pq02Kc0002	Chloro A	mg/lm				1	0.82	0.82	0.82	1980	1980		0.82										
Masson	Pq02Kc0002	Cl dis.	mg/l	2.43	1.56	135	10	1.00	3.54	1980	1988	3.42	4.13	5.83	4.18	3.57	2.91	2.91	2.61	2.74	2.59	2.86	3.89	4.74
Masson	Pq02Kc0002	Cond.	usie/c	435	21	209	140	7.40	82	1980	1988	86	85	107	96	84	74	74	69	67	70	72	84	100
Masson	Pq02Kc0002	Fe ex.	mg/l	0.081	0.28	65	2.30	0.070	0.27	1980	1983	0.44	0.23	0.16	0.69	0.18	0.18	0.21	0.22	0.18	0.20	0.24	0.26	0.21
Masson	Pq02Kc0002	Fe tot.	mg/l	0.011	0.10	61	0.92	0.11	0.21	1984	1988	0.21	0.19	0.21	0.43	0.22	0.18	0.18	0.21	0.18	0.15	0.16	0.21	0.20
Masson	Pq02Kc0002	HCO3 calc.	mg/l	40	6.33	15	45	21	32	1986	1987	29	30	33	41	21	29	29	26	35	39	45	33	37
Masson	Pq02Kc0002	Hg tot.	ug/l	0.38	0.61	8	1.80	0.050	0.28	1980	1981		0.050								0.97		0.050	
Masson	Pq02Kc0002	Mg tot.	mg/l	0.35	0.59	55	3.50	1.10	2.16	1980	1983	2.20	1.97	2.50	2.74	2.32	1.80	1.80	1.75	1.70	1.99	1.88	2.37	2.87
Masson	Pq02Kc0002	Mn ex.	mg/l	0.000	0.010	68	0.050	0.010	0.019	1980	1984	0.020	0.014	0.010	0.025	0.012	0.016	0.016	0.020	0.020	0.023	0.020	0.021	0.030
Masson	Pq02Kc0002	Mn tot.	mg/l	0.000	0.006	61	0.030	0.010	0.017	1984	1988	0.016	0.012	0.015	0.024	0.020	0.016	0.016	0.020	0.022	0.017	0.014	0.012	0.015
Masson	Pq02Kc0002	N dis.	mg/l	0.018	0.13	52	0.88	0.20	0.48	1985	1988	0.47	0.71	0.59	0.62	0.37	0.39	0.38	0.38	0.39	0.42	0.50	0.52	0.54
Masson	Pq02Kc0002	N dis.	mg/l	0.013	0.11	82	0.98	0.070	0.28	1980	1983	0.30	0.28	0.28	0.25	0.27	0.20	0.20	0.41	0.25	0.27	0.28	0.31	0.32
Masson	Pq02Kc0002	N tot. kjeld.	mg/l	0.006	0.076	79	0.56	0.090	0.29	1980	1985	0.29	0.35	0.29	0.27	0.27	0.28	0.28	0.29	0.26	0.26	0.31	0.31	0.28
Masson	Pq02La0002	NH4 dis.	mg/l	0.001	0.033	81	0.17	0.010	0.075	1980	1983	0.098	0.094	0.12	0.074	0.060	0.062	0.062	0.070	0.066	0.049	0.088	0.074	0.062
Masson	Pq02La0002	NH4 tot.	mg/l	0.002	0.042	133	0.18	0.004	0.070	1980	1988	0.086	0.094	0.081	0.056	0.053	0.060	0.060	0.067	0.052	0.051	0.086	0.074	0.073
Masson	Pq02La0002	NO2 + NO3 dis.	mg/l	0.005	0.068	213	0.42	0.020	0.18	1980	1988	0.19	0.20	0.25	0.24	0.16	0.16	0.14	0.13	0.11	0.12	0.16	0.22	0.29
Masson	Pq02La0002	O2 dis.	mg/l	7.84	2.80	20	19	7.50	12	1980	1985		14		13	12				8.85	7.70	11	13	
Masson	Pq02La0002	P susp.	ug/l	0.000	0.014	199	0.12	0.000	0.012	1980	1988	0.007	0.009	0.011	0.015	0.013	0.011	0.009	0.011	0.011	0.011	0.015	0.014	0.009

Appendix C

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	StDev	Cnt	Max	Min	Avg	First Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Masson	Pq02La0002	P tot.	mg/l	0.001	0.023	15	0.11	0.018	0.039	1986 1987	0.081	0.030	0.018	0.066	0.048	0.037	0.038	0.019	0.022	0.031	0.020	0.027
Masson	Pq02La0002	P tot. dis.	mg/l	0.000	0.012	161	0.10	0.006	0.018	1980 1985	0.022	0.020	0.021	0.016	0.010	0.013	0.022	0.010	0.014	0.017	0.024	0.026
Masson	Pq02La0002	pH	ph	0.065	0.26	147	7.70	6.30	7.22	1980 1988	7.16	7.26	7.30	7.33	7.33	7.27	7.18	7.18	7.04	7.17	7.15	7.38
Masson	Pq02La0002	PO4 dis.	mg/l	0.000	0.012	52	0.080	0.010	0.017	1985 1988	0.020	0.018	0.016	0.020	0.011	0.013	0.028	0.014	0.011	0.015	0.015	0.024
Masson	Pq02La0002	Sireact.	mg/l	0.56	0.75	75	5.80	1.00	4.38	1980 1985	4.75	4.96	4.46	5.16	4.67	4.14	4.09	3.77	3.63	4.00	4.20	4.63
Masson	Pq02La0002	SO4 dis.	mg/l	1.73	1.31	130	14	2.00	8.76	1980 1988	8.73	9.31	9.50	9.36	8.91	8.63	8.05	7.54	8.11	8.13	9.26	10
Masson	Pq02La0002	Sr. tot.	mg/l	0.000	0.010	4	0.060	0.040	0.047	1982 1983		0.050		0.060				0.040	0.040			
Masson	Pq02La0002	Temp	deg C	77	8.79	210	25	-2.000	10	1980 1988	-0.059	0.32	1.08	4.75	12	17	23	23	19	12	5.23	0.70
Hawkesbury	Pq02La0002	Alk tot. CaCO3	mg/l	62	7.85	33	44	0.10	23	1970 1984	21	21		14	28	25	20	20	20	26	23	25
Hawkesbury	Pq02La0002	BOD	mg/l	12	3.48	56	16	0.20	2.39	1972 1981	8.00	9.30	2.80	3.53	0.77	1.00	2.10	1.40	3.03	2.05	1.23	0.60
Hawkesbury	Pq02La0002	Cl dis.	mg/l	2.77	1.66	63	10	1.81	3.51	1972 1984	8.50	5.30	7.10	3.29	2.75	2.96	2.59	2.97	3.03	3.82	3.27	3.60
Hawkesbury	Pq02La0002	Cond.	usielc	94492	307	89	2860	6.00	126	1970 1984	96	90	115	648	77	174	77	81	82	85	91	91
Hawkesbury	Pq02La0002	Fe tot.	mg/l	0.14	0.37	10	1.40	0.27	0.53	1981 1984				0.99	0.38	0.84	0.44	0.26	0.34	0.45	0.46	
Hawkesbury	Pq02La0002	Hg ex.	ug/l	0.69	0.83	6	2.20	0.050	0.61	1970 1971	0.84	0.33									0.10	2.20
Hawkesbury	Pq02La0002	Hg tot.	ug/l	0.000	0.015	7	0.050	0.010	0.016	1984 1984				0.010	0.050	0.010	0.010	0.010	0.010	0.010	0.010	
Hawkesbury	Pq02La0002	Mg tot.	mg/l	0.31	0.56	7	3.02	1.60	1.99	1984 1984				3.02	2.50	1.60	1.64	1.60	1.82		1.72	
Hawkesbury	Pq02La0002	Mn tot.	mg/l	0.000	0.006	7	0.037	0.021	0.026	1984 1984				0.037	0.021	0.027	0.031	0.024	0.022		0.021	
Hawkesbury	Pq02La0002	N tot.	mg/l	6.49	2.55	57	20	0.30	1.15	1972 1984	1.57	1.59	1.05	5.43	0.68	0.57	0.66	0.74	0.88	0.92	0.59	0.69
Hawkesbury	Pq02La0002	N tot. kjeld.	mg/l	0.18	0.43	134	2.65	0.10	0.53	1970 1984	0.91	1.01	0.64	0.52	0.35	0.38	0.52	0.52	0.55	0.63	0.40	0.43
Hawkesbury	Pq02La0002	NH4 dis.	mg/l	0.071	0.27	65	1.29	0.006	0.17	1972 1984	0.87	0.56	0.26	0.13	0.039	0.089	0.14	0.20	0.23	0.13	0.022	0.019
Hawkesbury	Pq02La0002	NO2 + NO3 dis.	mg/l	0.005	0.071	8	0.38	0.17	0.25	1970 1971	0.17	0.20								0.18	0.26	0.34
Hawkesbury	Pq02La0002	NO3 dis.	mg/l	5.50	2.35	63	19	0.020	0.47	1972 1984	0.13	0.17	0.27	4.84	0.29	0.14	0.090	0.090	0.13	0.20	0.20	0.31
Hawkesbury	Pq02La0002	NO3 dis.	mg/l	0.000	0.012	64	0.10	0.003	0.008	1972 1984	0.009	0.006	0.007	0.006	0.018	0.008	0.007	0.007	0.007	0.008	0.005	0.004
Hawkesbury	Pq02La0002	O2 dis.	mg/l	6.33	2.52	71	15	4.30	9.81	1972 1984	14	9.60	12	12	10	9.00	7.89	7.54	8.97	10	12	13
Hawkesbury	Pq02La0002	P tot.	mg/l	0.016	0.13	71	1.10	0.009	0.054	1970 1984	0.036	0.061	0.056	0.035	0.036	0.033	0.20	0.033	0.038	0.043	0.030	0.031
Hawkesbury	Pq02La0002	pH	ph	1.01	1.00	33	8.70	2.28	6.97	1970 1984	6.90	6.80		4.70	7.56	7.19	7.30	7.25	6.83	6.94	7.07	7.30
Hawkesbury	Pq02La0002	PO4 dis.	mg/l	0.000	0.014	58	0.10	0.001	0.010	1972 1981	0.005	0.004	0.014	0.007	0.006	0.010	0.015	0.007	0.018	0.012	0.008	0.004
Hawkesbury	Pq02La0002	Temp	deg C	67	8.19	89	27	0.000	13	1970 1984	6.07	12	1.78	5.96	12	20	20	22	18	11	9.54	9.07
Carillon	Pq02La0002	Al ex.	mg/l	0.011	0.10	22	0.37	0.080	0.21	1982 1985		0.19		0.34	0.25			0.10	0.087		0.23	
Carillon	Pq02La0002	Alk tot. CaCO3	mg/l	48	6.89	160	43	5.00	24	1978 1988	22	22	24	29	23	21	22	21	20	27	26	30
Carillon	Pq02La0002	C dis.	mg/l	3.31	1.82	82	10	2.20	5.99	1984 1988	6.13	5.95	7.22	8.63	5.94	5.60	4.55	4.83	5.43	6.40	5.65	6.22
Carillon	Pq02La0002	C dis.	mg/l	0.40	0.63	85	7.40	3.60	5.77	1984 1988	6.03	5.59	5.57	5.26	5.61	5.67	5.68	5.87	6.04	5.87	6.00	6.13
Carillon	Pq02La0002	C tot.	mg/l	14	3.77	258	31	11	18	1978 1983	20	18	18	18	16	15	17	19	16	16	19	20
Carillon	Pq02La0002	C tot. inorg.	mg/l	2.94	1.71	258	11	0.50	5.64	1978 1983	6.06	5.52	5.93	6.59	4.95	4.34	4.47	5.02	5.15	5.36	6.73	7.23
Carillon	Pq02La0002	Ca dis.	mg/l			1	8.00	8.00	8.00	1979 1979	8.00											
Carillon	Pq02La0002	Ca tot.	mg/kg	4.33	2.08	4	11	6.70	9.70	1983 1983		11		9.90					6.70		11	

Appendix C

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	SD	Dev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Carillon	Pq02Lb0002	Ca tot.	mg/l	4.72	2.17	187	1	0.56	2.70	9.40	1979	1988	9.21	8.62	9.63	11	9.20	8.71	7.60	8.52	8.90	9.17	10	11
Carillon	Pq02Lb0002	Chloro A	mg/m				1	0.56	0.56	0.56	1980	1980												
Carillon	Pq02Lb0002	Cl dis.	mg/l	1.42	1.19	199	1	7.00	2.00	3.51	1979	1988	3.31	3.69	3.61	4.05	3.32	2.66	2.81	3.01	3.28	3.61	4.10	4.36
Carillon	Pq02Lb0002	Cond.	usie/c	352	19	326	140	6.00	86	86	1978	1988	85	85	92	98	81	78	70	76	75	89	98	97
Carillon	Pq02Lb0002	Fe ex.	mg/l	0.054	0.23	133	1.68	0.090	0.30	0.30	1979	1983	0.21	0.26	0.21	0.68	0.20	0.27	0.21	0.20	0.27	0.21	0.35	0.24
Carillon	Pq02Lb0002	Fe tot.	mg/l	0.026	0.16	75	1.19	0.10	0.28	0.28	1979	1988	0.22	0.22	0.22	0.61	0.32	0.25	0.23	0.25	0.24	0.19	0.27	0.26
Carillon	Pq02Lb0002	HCO3 calc.	mg/l	68	8.22	14	49	23	35	35	1986	1987	32	28	29	39	23	37	29	43	41	49	42	45
Carillon	Pq02Lb0002	Hg ex.	ug/l	0.000	0.000	4	0.050	0.050	0.050	0.050	1979	1979		0.050		0.050					0.050		0.050	
Carillon	Pq02Lb0002	Hg tot.	ug/l	0.002	0.040	8	0.15	0.050	0.071	0.071	1980	1981		0.050		0.050					0.14		0.050	
Carillon	Pq02Lb0002	K dis.	mg/l	0.20	0.45	23	2.40	0.80	1.12	1.12	1979	1982		1.00	0.80	1.53	0.80	0.90	0.80	0.85	1.02	1.00	1.41	1.00
Carillon	Pq02Lb0002	Mg dis.	mg/l			1	1.90	1.90	1.90	1.90	1979	1979		1.90										
Carillon	Pq02Lb0002	Mg tot.	mg/l	0.41	0.64	132	4.00	1.50	2.39	2.39	1979	1983	2.16	2.09	2.27	2.94	2.33	2.21	1.96	2.22	2.13	2.31	2.81	2.67
Carillon	Pq02Lb0002	Mn ex.	mg/l	0.004	0.066	132	0.55	0.010	0.030	0.030	1979	1984	0.015	0.018	0.017	0.029	0.023	0.025	0.037	0.021	0.091	0.012	0.017	0.025
Carillon	Pq02Lb0002	Mn tot.	mg/l	0.000	0.011	75	0.080	0.010	0.021	0.021	1979	1988	0.015	0.011	0.016	0.027	0.026	0.022	0.035	0.027	0.023	0.012	0.015	0.016
Carillon	Pq02Lb0002	N dis.	mg/l	0.019	0.14	51	1.04	0.27	0.50	0.50	1985	1988	0.52	0.55	0.62	0.73	0.42	0.47	0.37	0.46	0.46	0.46	0.45	0.56
Carillon	Pq02Lb0002	N dis.	mg/l	0.011	0.11	113	0.97	0.13	0.30	0.30	1979	1983	0.30	0.30	0.28	0.34	0.24	0.27	0.24	0.34	0.30	0.27	0.32	0.39
Carillon	Pq02Lb0002	N tot. kjeld.	mg/l	0.008	0.091	183	0.94	0.13	0.30	0.30	1978	1985	0.33	0.31	0.31	0.30	0.26	0.28	0.28	0.33	0.29	0.30	0.30	0.27
Carillon	Pq02Lb0002	Na dis.	mg/l	0.46	0.68	24	4.70	2.00	3.01	3.01	1979	1982		3.45	2.80	3.05	2.55	2.00	2.70	2.75	3.20	3.10	3.13	3.40
Carillon	Pq02Lb0002	NH4 dis.	mg/l	0.001	0.034	145	0.18	0.020	0.082	0.082	1979	1983	0.11	0.10	0.093	0.089	0.059	0.069	0.078	0.12	0.082	0.078	0.058	0.076
Carillon	Pq02Lb0002	NH4 tot.	mg/l	0.003	0.051	203	0.39	0.002	0.077	0.077	1978	1988	0.13	0.079	0.096	0.076	0.050	0.062	0.083	0.078	0.070	0.059	0.060	0.065
Carillon	Pq02Lb0002	NO2 + NO3 dis.	mg/l	0.006	0.074	347	0.59	0.090	0.21	0.21	1978	1988	0.22	0.22	0.26	0.27	0.18	0.15	0.14	0.13	0.15	0.19	0.26	0.29
Carillon	Pq02Lb0002	O2 dis.	mg/l	8.55	2.92	37	15	5.60	11	11	1979	1985		13		13	13			7.30	6.70		11	
Carillon	Pq02Lb0002	P susp.	ug/l	0.000	0.015	215	0.11	0.000	0.013	0.013	1980	1988	0.011	0.010	0.022	0.020	0.012	0.014	0.008	0.012	0.009	0.011	0.013	0.009
Carillon	Pq02Lb0002	P tot.	mg/l	0.001	0.023	15	0.090	0.006	0.035	0.035	1978	1987	0.062	0.027	0.018	0.072	0.037	0.054	0.021	0.021	0.053	0.026	0.017	0.014
Carillon	Pq02Lb0002	P tot. dis.	mg/l	0.000	0.017	265	0.15	0.006	0.019	0.019	1979	1985	0.026	0.014	0.017	0.021	0.011	0.033	0.016	0.024	0.017	0.012	0.019	0.014
Carillon	Pq02Lb0002	pH	ph	0.084	0.29	221	8.50	6.30	7.14	7.14	1978	1988	7.15	7.14	7.15	7.20	7.23	7.14	7.05	7.05	7.01	7.22	7.18	7.18
Carillon	Pq02Lb0002	PO4 dis.	mg/l	0.000	0.016	51	0.12	0.010	0.017	0.017	1985	1988	0.012	0.017	0.015	0.025	0.012	0.017	0.032	0.017	0.016	0.014	0.010	0.011
Carillon	Pq02Lb0002	Si react.	mg/l	0.60	0.78	124	5.70	2.20	4.22	4.22	1979	1985	4.68	4.76	4.64	4.39	4.53	3.70	3.68	3.57	3.50	3.90	4.25	4.66
Carillon	Pq02Lb0002	SO4 dis.	mg/l	2.50	1.58	201	15	7.00	9.66	9.66	1979	1988	9.51	10	9.85	9.36	9.26	8.83	8.71	8.94	9.14	10	11	12
Carillon	Pq02Lb0002	Sr. tot.	mg/l	0.000	0.009	8	0.060	0.040	0.047	0.047	1982	1983		0.040		0.060				0.040	0.050			
Carillon	Pq02Lb0002	Temp	deg C	69	8.33	381	25	0.000	9.71	9.71	1979	1988	0.067	0.82	0.73	4.55	12	18	22	22	19	13	6.28	2.88
Carillon 2	Qu02Lb0012	Al ex.	mg/l	0.005	0.068	20	0.31	0.080	0.15	0.15	1989	1990	0.057	0.13	0.20	0.25	0.10	0.13	0.13	0.090	0.090	0.15	0.23	0.14
Carillon 2	Qu02Lb0012	Alk tot. CaCO3	mg/l	48	6.95	10	40	17	23	23	1988	1988				40	25	18	19	19	17	18	26	20
Carillon 2	Qu02Lb0012	C dis.	mg/l	0.24	0.49	30	6.80	5.20	6.00	6.00	1988	1990	6.60	6.00	5.80	5.40	6.10	6.20	5.87	5.30	5.70	6.00	6.20	6.37
Carillon 2	Qu02Lb0012	Ca tot	mg/l	2.49	1.58	21	14	7.10	8.50	8.50	1988	1989	7.60	7.80	7.70	12	9.37	7.65	8.00	7.50	7.55	7.80	9.70	7.80
Carillon 2	Qu02Lb0012	Cl dis.	mg/l	2.50	1.58	9	7.00	2.00	3.67	3.67	1989	1989	7.00	3.00	2.00	5.00	4.00	2.00	3.50					

Table C1: Mean monthly chemistry of selected stations along the Ottawa River, 1970-90 (calculated from Environment Canada, 1993a)

River St.	Station no.	Variable	Unit	Var	SD	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Carillon 2	Qu02Lb0012	Cond.	us/c	267	16	30	132	65	84	1988	1990	90	82	93	115	87	68	73	74	70	72	86	81
Carillon 2	Qu02Lb0012	Fe tot.	mg/l	0.009	0.094	30	0.47	0.070	0.22	1988	1990	0.18	0.19	0.31	0.40	0.18	0.19	0.16	0.19	0.16	0.24	0.32	0.18
Carillon 2	Qu02Lb0012	Mn tot.	mg/l	0.000	0.008	30	0.030	0.010	0.019	1988	1990	0.013	0.010	0.020	0.030	0.017	0.025	0.023	0.025	0.020	0.016	0.020	0.017
Carillon 2	Qu02Lb0012	N dis.	mg/l	0.015	0.12	30	0.76	0.27	0.49	1988	1990	0.57	0.44	0.55	0.69	0.53	0.42	0.38	0.38	0.35	0.44	0.62	0.52
Carillon 2	Qu02Lb0012	NH4 dis.	mg/l	0.001	0.023	36	0.11	0.020	0.058	1988	1990	0.047	0.078	0.074	0.11	0.043	0.050	0.067	0.055	0.045	0.035	0.030	0.047
Carillon 2	Qu02Lb0012	NO2 + NO3 dis.	mg/l	0.010	0.098	30	0.54	0.090	0.22	1988	1990	0.27	0.28	0.25	0.35	0.22	0.14	0.11	0.11	0.14	0.20	0.32	0.23
Carillon 2	Qu02Lb0012	P susp.	ug/l	0.000	0.018	30	0.10	0.007	0.021	1988	1990	0.025	0.012	0.020	0.068	0.027	0.020	0.015	0.013	0.010	0.010	0.019	0.012
Carillon 2	Qu02Lb0012	pH	ph	0.068	0.26	21	7.60	6.70	7.06	1988	1989	7.00	6.90	6.70	7.35	7.30	7.00	6.90	6.90	7.00	7.10	7.30	7.10
Carillon 2	Qu02Lb0012	PO4 dis.	mg/l	0.001	0.027	30	0.14	0.010	0.021	1988	1990	0.027	0.012	0.017	0.015	0.010	0.010	0.053	0.010	0.017	0.018	0.013	0.033
Carillon 2	Qu02Lb0012	SO4 dis.	mg/l	0.77	0.88	21	12	7.50	8.88	1988	1989	8.50	9.50	8.50	10	9.00	9.00	8.50	8.75	8.50	8.50	9.50	8.50
Carillon 2	Qu02Lb0012	Temp	deg C	77	8.79	36	25	0.000	7.96	1988	1990	0.50	0.74	1.80	2.50	12	19	24	23	18	11	5.67	0.67

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StdDev	Crit	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bonnechere	On02Kc0001	Al ex.	mg/l	0.002	0.042	3	0.080	0.000	0.047	1971	1971						0.050					0.080	
Bonnechere	On02Kc0001	Alk tot. CaCO3	mg/l	259	16	104	116	13	67	1970	1984	70	67	65	65	66	73	57	60	52	76	81	75
Bonnechere	On02Kc0001	BOD	mg/l	2.28	1.51	69	8.00	0.20	1.41	1970	1979	2.45	3.36	4.83	2.37	1.07	0.97	0.57	0.40	0.63	0.90	1.23	1.00
Bonnechere	On02Kc0001	Ca tot.	mg/l	19	4.31	13	32	18	23	1970	1971				21	23	23	18	23	22	26	32	
Bonnechere	On02Kc0001	Cl dis.	mg/l	24	4.92	72	42	2.00	5.53	1970	1984	6.37	9.63	5.06	9.60	4.33	4.86	3.69	3.76	3.71	6.15	6.56	3.60
Bonnechere	On02Kc0001	Cond.	usie/c	2502	50	113	520	62	174	1970	1984	185	226	165	186	166	178	146	150	141	187	195	192
Bonnechere	On02Kc0001	daily av. disch.	m3/s	587	24	76	109	3.91	25	1972	1981	15	14	64	57	55	27	17	9.94	8.66	12	23	14
Bonnechere	On02Kc0001	Fe ex.	mg/l	6.12	2.47	7	6.90	0.15	1.31	1970	1971				6.90	0.63	0.30			0.15	0.35	0.25	
Bonnechere	On02Kc0001	Fe tot.	mg/l	0.59	0.77	90	5.30	0.050	0.48	1972	1984	0.21	0.26	0.92	1.21	1.17	0.40	0.45	0.17	0.22	0.23	0.25	0.33
Bonnechere	On02Kc0001	Hg tot.	ug/l	0.001	0.024	11	0.080	0.010	0.032	1977	1984	0.080		0.060	0.040		0.010		0.030	0.020	0.015	0.020	
Bonnechere	On02Kc0001	HIN4 ds.	mg/l	0.003	0.053	101	0.41	0.002	0.044	1972	1984	0.046	0.066	0.15	0.036	0.028	0.043	0.030	0.021	0.037	0.040	0.035	0.057
Bonnechere	On02Kc0001	K ds.	mg/l	0.37	0.61	13	3.50	1.20	1.53	1970	1971				3.50	1.40	1.35	1.30	1.30	1.20	1.50	1.40	
Bonnechere	On02Kc0001	Mg ds.	mg/l	3.27	1.81	13	7.00	1.00	4.46	1970	1971				7.00	4.33	4.00	5.00	3.00	2.00	5.50	6.00	
Bonnechere	On02Kc0001	Mg tot.	mg/l	17	4.14	57	34	1.00	6.21	1972	1984	6.07	6.75	7.13	5.27	4.57	10	6.02	5.18	4.20	6.13	7.08	5.00
Bonnechere	On02Kc0001	Mn ex.	mg/l	0.001	0.038	4	0.10	0.010	0.058	1970	1971				0.10	0.010	0.050					0.070	
Bonnechere	On02Kc0001	Mn tot.	mg/l	0.002	0.044	54	0.28	0.009	0.043	1972	1984	0.029	0.14	0.051	0.065	0.050	0.039	0.035	0.023	0.033	0.032	0.029	0.014
Bonnechere	On02Kc0001	N tot.	mg/l	0.39	0.62	66	5.08	0.32	0.67	1972	1984	1.47	1.04	0.87	0.69	0.61	0.64	0.49	0.45	0.46	0.54	0.48	0.44
Bonnechere	On02Kc0001	N tot. kjeld.	mg/l	0.32	0.56	151	5.00	0.17	0.53	1970	1984	1.34	0.79	0.57	0.55	0.52	0.50	0.41	0.39	0.39	0.41	0.40	0.33
Bonnechere	On02Kc0001	Na ds.	mg/l	0.59	0.77	13	5.00	3.00	3.62	1970	1971				4.00	3.00	4.00	3.00	3.50	3.00	4.00	5.00	
Bonnechere	On02Kc0001	NH4 tot.	mg/l	0.005	0.068	12	0.27	0.020	0.064	1970	1971				0.27	0.030	0.055	0.060	0.035	0.040	0.045	0.070	
Bonnechere	On02Kc0001	NO3 + NO2	mg/l	0.014	0.12	12	0.44	0.005	0.082	1970	1971				0.44	0.040	0.13	0.005	0.030	0.070	0.065	0.050	
Bonnechere	On02Kc0001	NO3 ds.	mg/l	0.011	0.11	71	0.49	0.005	0.10	1972	1984	0.11	0.20	0.24	0.18	0.071	0.10	0.064	0.036	0.035	0.092	0.085	0.087
Bonnechere	On02Kc0001	NO3 ds.	mg/l	0.002	0.049	84	0.45	0.000	0.014	1970	1984	0.004	0.005	0.018	0.012	0.005	0.014	0.063	0.008	0.013	0.009	0.004	0.004
Bonnechere	On02Kc0001	O2 ds.	mg/l	9.06	3.01	110	19	2.00	12	1970	1984	14	12	15	12	10	11	10	10	9.88	12	14	15
Bonnechere	On02Kc0001	P tot.	mg/l	0.003	0.054	112	0.29	0.001	0.052	1970	1984	0.070	0.068	0.085	0.078	0.054	0.053	0.051	0.044	0.032	0.048	0.025	0.038
Bonnechere	On02Kc0001	pH	ph	0.094	0.31	106	8.58	6.90	7.82	1970	1984	7.62	7.60	7.77	7.82	7.87	7.89	7.93	7.97	7.76	7.77	7.92	7.86
Bonnechere	On02Kc0001	PO4 ds.	mg/l	0.001	0.028	63	0.16	0.001	0.026	1972	1980	0.064	0.021	0.027	0.015	0.031	0.019	0.028	0.021	0.022	0.036	0.013	0.015
Bonnechere	On02Kc0001	PO4 ds. ortho	mg/l	0.000	0.010	13	0.039	0.002	0.013	1970	1971				0.039	0.003	0.012	0.016	0.016	0.016	0.013	0.010	
Bonnechere	On02Kc0001	Si react.	mg/l	1.08	1.04	13	7.30	4.00	5.39	1970	1971				4.90	5.43	5.45	5.70	6.20	4.00	4.45	7.00	
Bonnechere	On02Kc0001	SO4 ds.	mg/l	7.69	2.77	13	20	10	14	1970	1971				11	15	12	11	16	12	16	14	
Bonnechere	On02Kc0001	Temp.	deg c	75	8.67	113	27	0.000	11	1970	1984	0.70	0.50	0.97	6.48	12	20	21	22	19	10	3.62	1.13
Coulange	Pq02Kc0002	Al ex.	mg/l	0.007	0.081	13	0.33	0.050	0.14	1982	1985		0.14			0.19			0.10		0.12		
Coulange	Pq02Kc0002	Alk tot. CaCO3	mg/l	135	12	81	88	2.50	10	1979	1988	9.15	16	15	5.13	4.82	7.63	10	11	25	6.00	8.21	6.45
Coulange	Pq02Kc0002	C ds. inorg.	mg/l	1.36	1.17	77	6.80	0.60	2.19	1984	1988	2.80	2.95	3.16	1.72	1.51	2.53	2.58	1.38	1.92	1.61	1.74	2.02

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	SD	Dev	Crit	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coulange	Pq02Kg0002	C ds. org.	mg/l	17	4.13	77	40	2.00	6.49	1984	1988	4.98	5.39	4.82	12	6.04	5.65	6.98	7.00	6.46	7.00	6.62	6.33	
Coulange	Pq02Kg0002	C tot.	mg/l	31	5.55	121	48	7.00	14	1979	1983	18	16	13	13	15	13	13	14	14	13	13	16	
Coulange	Pq02Kg0002	C tot. inorg.	mg/l	6.77	2.60	121	18	0.50	2.71	1979	1983	3.85	4.64	3.78	1.56	1.00	1.44	2.43	3.68	3.45	1.61	1.61	2.10	
Coulange	Pq02Kg0002	Ca ds.	mg/l				1	5.30	5.30	5.30	1979	1979		5.30										
Coulange	Pq02Kg0002	Ca tot.	mg/l	2.66	1.63	104	12	0.000	4.79	1979	1988	4.63	5.46	5.92	4.16	3.87	4.75	5.37	4.94	5.91	3.80	4.53	5.18	
Coulange	Pq02Kg0002	Cl ds.	mg/l	50	7.07	115	64	0.20	2.96	1979	1988	1.63	2.26	4.60	1.24	1.77	6.30	3.47	1.52	8.90	1.19	1.84	2.17	
Coulange	Pq02Kg0002	Cond.	usiel/c	1023	32	186	290	0.000	50	1979	1988	48	57	66	36	37	58	56	49	82	38	41	47	
Coulange	Pq02Kg0002	Fe ex.	mg/l	0.035	0.19	58	1.29	0.040	0.30	1979	1983	0.17	0.46	0.28	0.25	0.23	0.21	0.39	0.31	0.46	0.25	0.25	0.31	
Coulange	Pq02Kg0002	Fe tot.	mg/l	0.017	0.13	62	0.95	0.090	0.29	1979	1988	0.25	0.27	0.29	0.32	0.33	0.35	0.23	0.24	0.27	0.29	0.30	0.29	
Coulange	Pq02Kg0002	HCO3 calc.	mg/l	14	3.77	14	17	4.30	10	1986	1987	11	14	17	4.30	5.40	8.50	14	11	11		7.30	11	
Coulange	Pq02Kg0002	Hg ex.	ug/l	0.000	0.000	4	0.050	0.050	0.050	1979	1979		0.050			0.050			0.050		0.050			
Coulange	Pq02Kg0002	HN4 dis.	mg/l	0.001	0.033	78	0.19	0.010	0.045	1979	1983	0.070	0.066	0.075	0.057	0.048	0.027	0.045	0.030	0.040	0.038	0.032	0.030	
Coulange	Pq02Kg0002	K ds.	mg/l	0.064	0.25	33	1.60	0.50	0.83	1979	1983	0.70	0.83	1.20	0.83	0.67	0.80	1.25	0.82	1.20	0.65	1.20	0.50	
Coulange	Pq02Kg0002	Mg ds.	mg/l				1	1.00	1.00	1.00	1979	1979		1.00										
Coulange	Pq02Kg0002	Mg tot.	mg/l	0.24	0.49	66	3.70	0.000	1.08	1979	1983	1.10	1.44	1.27	0.84	0.81	0.88	1.23	1.11	1.44	0.83	1.15	1.07	
Coulange	Pq02Kg0002	Mn ex.	mg/l	0.002	0.047	61	0.34	0.010	0.037	1979	1984	0.017	0.027	0.023	0.040	0.025	0.020	0.055	0.032	0.12	0.023	0.027	0.045	
Coulange	Pq02Kg0002	Mn. tot.	mg/l	0.003	0.056	62	0.45	0.010	0.030	1979	1988	0.017	0.016	0.017	0.040	0.034	0.093	0.027	0.025	0.025	0.017	0.017	0.017	
Coulange	Pq02Kg0002	N ds.	mg/l	0.024	0.16	48	0.97	0.18	0.38	1985	1988	0.42	0.41	0.56	0.50	0.44	0.39	0.35	0.26	0.28	0.31	0.30	0.40	
Coulange	Pq02Kg0002	N ds. kjeld.	mg/l	0.032	0.18	44	1.22	0.14	0.29	1979	1983	0.36	0.22	0.22	0.31	0.31	0.25	0.48	0.28	0.25	0.25	0.28		
Coulange	Pq02Kg0002	N tot. kjeld.	mg/l	0.042	0.21	108	1.56	0.11	0.31	1979	1985	0.34	0.38	0.30	0.25	0.41	0.27	0.27	0.25	0.37	0.28	0.23	0.31	
Coulange	Pq02Kg0002	Na ds.	mg/l	0.94	0.97	33	5.10	0.50	1.49	1979	1983	1.60	1.98	2.90	1.20	0.87	1.40	1.90	2.02	1.50	1.15	0.80	0.90	
Coulange	Pq02Kg0002	NH4 tot.	mg/l	0.004	0.066	120	0.60	0.001	0.052	1979	1988	0.081	0.087	0.050	0.048	0.024	0.043	0.049	0.019	0.078	0.029	0.029	0.052	
Coulange	Pq02Kg0002	NO3 + NO2	mg/l	0.053	0.23	199	2.30	0.020	0.15	1979	1988	0.32	0.18	0.39	0.19	0.13	0.061	0.035	0.034	0.084	0.071	0.086	0.28	
Coulange	Pq02Kg0002	O2 ds.	mg/l	3.94	1.98	18	15	8.50	12	1979	1985		14		15	12			9.20		13			
Coulange	Pq02Kg0002	P ds. tot.	mg/l	0.000	0.009	117	0.045	0.006	0.013	1979	1985	0.011	0.014	0.015	0.014	0.014	0.014	0.018	0.012	0.016	0.008	0.008	0.010	
Coulange	Pq02Kg0002	P susp.	ug/l	0.000	0.006	60	0.027	0.000	0.002	1984	1988	0.003	0.003	0.000	0.004	0.003	0.005	0.004	0.000	0.000	0.001	0.003	0.000	
Coulange	Pq02Kg0002	P tot.	mg/l	0.000	0.018	15	0.063	0.000	0.017	1986	1987	0.014	0.006	0.009	0.063	0.038	0.019	0.011	0.000	0.012	0.014	0.013	0.024	
Coulange	Pq02Kg0002	pH	ph	0.13	0.35	122	8.10	5.90	6.90	1979	1988	6.84	6.97	6.92	6.81	6.75	6.86	6.85	7.18	6.98	6.86	6.84	6.87	
Coulange	Pq02Kg0002	PO4 ds.	mg/l	0.000	0.004	48	0.035	0.010	0.011	1985	1988	0.015	0.010	0.010	0.010	0.012	0.015	0.010	0.010	0.010	0.010	0.012	0.010	
Coulange	Pq02Kg0002	Si react.	mg/l	4.80	2.19	53	13	0.70	4.14	1979	1985	3.74	6.99	3.42	4.70	4.02	3.58	3.55	3.26	2.50	3.50	3.17	5.60	
Coulange	Pq02Kg0002	SO4 ds.	mg/l	1.91	1.38	116	13	4.50	7.21	1979	1988	7.76	8.59	8.39	6.89	6.26	6.80	6.46	7.01	7.00	6.65	7.37	7.77	
Coulange	Pq02Kg0002	Sr tot.	mg/l	0.000	0.015	3	0.060	0.030	0.047	1982	1983		0.050			0.030			0.060					
Coulange	Pq02Kg0002	Temp.	deg c	77	8.78	224	29	0.000	10	1979	1988	0.48	0.61	2.12	4.63	11	19	22	22	18	9.69	3.35	0.17	
Gatineau	Pq02Lh0004	Al ex.	mg/l	0.004	0.065	20	0.25	0.050	0.12	1982	1985		0.095		0.22	0.11			0.063	0.15	0.060	0.10		

Table C.2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StdDev	Crit	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gatineau	Pq02Lh0004	Alk tot. CaCO3	mg/l	15	3.91	165	25	1.40	12	1976	1988	11	9.82	11	18	17	11	12	12	11	12	11	13
Gatineau	Pq02Lh0004	C ds. inorg.	mg/l	1.18	1.09	83	6.20	1.60	3.12	1984	1988	2.46	2.65	3.44	5.50	4.56	3.04	2.80	2.64	2.72	2.41	2.47	2.72
Gatineau	Pq02Lh0004	C ds. org.	mg/l	0.53	0.73	85	7.00	2.80	5.20	1984	1988	5.43	4.88	4.77	4.67	4.42	5.17	5.36	5.83	5.88	5.27	5.26	5.82
Gatineau	Pq02Lh0004	C tot.	mg/l	21	4.55	294	44	5.50	13	1976	1983	15	12	12	13	13	12	12	15	15	12	12	12
Gatineau	Pq02Lh0004	C tot. inorg.	mg/l	1.33	1.15	294	6.00	0.50	3.01	1976	1983	3.42	2.61	3.26	3.85	3.52	2.78	2.98	2.77	2.68	2.65	2.60	3.29
Gatineau	Pq02Lh0004	Ca ds.	mg/l	0.18	0.42	2	5.20	4.60	4.90	1976	1979		4.60									5.20	
Gatineau	Pq02Lh0004	Ca tot.	mg/l	3.59	1.90	361	17	1.50	5.86	1973	1988	4.79	5.55	6.07	8.16	7.73	6.09	5.41	5.48	4.80	4.92	5.20	5.58
Gatineau	Pq02Lh0004	chloro A	mg/m			1	0.62	0.62	0.62	1980	1980		0.62										
Gatineau	Pq02Lh0004	Cl ds.	mg/l	5.38	2.32	373	32	0.10	1.42	1973	1988	1.11	2.83	1.53	1.88	1.49	1.20	0.93	0.94	1.03	1.10	1.22	1.31
Gatineau	Pq02Lh0004	Cond.	usie/c	574	24	516	455	15	49	1973	1988	42	48	51	66	58	49	45	42	39	42	45	58
Gatineau	Pq02Lh0004	Fe ex.	mg/l	0.018	0.13	132	0.79	0.030	0.25	1980	1983	0.15	0.29	0.21	0.42	0.18	0.18	0.18	0.21	0.23	0.27	0.35	0.26
Gatineau	Pq02Lh0004	Fe tot.	mg/l	0.047	0.22	84	1.17	0.090	0.29	1975	1988	0.23	0.22	0.26	0.72	0.20	0.19	0.20	0.25	0.19	0.28	0.22	0.27
Gatineau	Pq02Lh0004	HCO3 calc.	mg/l	17	4.09	14	24	11	15	1986	1987	11	11	13	22	24	16	13		16	16	16	12
Gatineau	Pq02Lh0004	Hg ex.	ug/l	0.000	0.000	7	0.050	0.050	0.050	1976	1979		0.050		0.050					0.050	0.050	0.050	0.050
Gatineau	Pq02Lh0004	Hg tot.	ug/l	0.001	0.025	8	0.11	0.050	0.068	1980	1981		0.050		0.050					0.10	0.070	0.070	
Gatineau	Pq02Lh0004	HN4 ds.	mg/l	0.000	0.012	168	0.070	0.010	0.030	1976	1983	0.025	0.028	0.024	0.040	0.024	0.030	0.030	0.041	0.028	0.031	0.027	0.023
Gatineau	Pq02Lh0004	K ds.	mg/l	0.056	0.24	203	2.50	0.10	0.69	1973	1983	0.51	0.60	0.69	0.90	0.78	0.70	0.69	0.80	0.68	0.62	0.73	0.55
Gatineau	Pq02Lh0004	Mg ds.	mg/l	0.020	0.14	2	1.10	0.90	1.00	1976	1979		0.90									1.10	
Gatineau	Pq02Lh0004	Mg tot.	mg/l	0.13	0.36	308	4.20	0.30	1.12	1973	1983	0.90	1.10	1.14	1.51	1.31	1.16	1.07	1.10	0.96	0.99	1.10	1.06
Gatineau	Pq02Lh0004	Mn ex.	mg/l	0.001	0.029	136	0.20	0.010	0.024	1980	1984	0.010	0.025	0.017	0.016	0.016	0.044	0.020	0.025	0.029	0.047	0.022	0.019
Gatineau	Pq02Lh0004	Mn. tot.	mg/l	0.000	0.014	84	0.080	0.010	0.022	1975	1988	0.013	0.012	0.014	0.032	0.020	0.030	0.025	0.041	0.023	0.021	0.011	0.016
Gatineau	Pq02Lh0004	N ds.	mg/l	0.006	0.079	50	0.57	0.10	0.32	1985	1988	0.31	0.36	0.40	0.41	0.34	0.28	0.28	0.30	0.28	0.32	0.25	0.31
Gatineau	Pq02Lh0004	N ds. kjeld.	mg/l	0.003	0.059	131	0.42	0.050	0.19	1976	1983	0.18	0.15	0.16	0.18	0.17	0.22	0.19	0.20	0.19	0.19	0.19	0.25
Gatineau	Pq02Lh0004	N tot. kjeld.	mg/l	0.008	0.089	200	0.73	0.050	0.20	1978	1985	0.26	0.16	0.17	0.23	0.19	0.20	0.19	0.21	0.20	0.22	0.18	0.19
Gatineau	Pq02Lh0004	Na ds.	mg/l	0.99	0.99	204	14	0.40	1.31	1973	1983	1.19	1.16	1.33	1.88	1.42	1.18	1.06	1.95	1.11	1.15	1.16	1.17
Gatineau	Pq02Lh0004	NH4 tot.	mg/l	0.001	0.034	214	0.33	0.001	0.032	1978	1988	0.070	0.026	0.028	0.042	0.023	0.026	0.031	0.031	0.026	0.034	0.021	0.022
Gatineau	Pq02Lh0004	NO3 + NO2	mg/l	0.047	0.22	524	2.90	0.020	0.18	1973	1988	0.21	0.27	0.30	0.22	0.21	0.15	0.12	0.12	0.13	0.14	0.14	0.17
Gatineau	Pq02Lh0004	O2 ds.	mg/l	3.77	1.94	34	14	8.10	11	1976	1985		13		12	11			9.00	8.40	11	12	
Gatineau	Pq02Lh0004	P ds. tot.	mg/l	0.000	0.017	260	0.12	0.006	0.014	1979	1985	0.021	0.009	0.018	0.020	0.008	0.009	0.021	0.009	0.018	0.008	0.012	0.010
Gatineau	Pq02Lh0004	P susp.	ug/l	0.000	0.010	209	0.084	0.000	0.008	1980	1988	0.011	0.006	0.011	0.013	0.011	0.008	0.004	0.006	0.007	0.008	0.007	0.005
Gatineau	Pq02Lh0004	P tot.	mg/l	0.000	0.018	33	0.075	0.006	0.018	1976	1987	0.047	0.013	0.012	0.050	0.049	0.027	0.024	0.007	0.009	0.013	0.010	0.008
Gatineau	Pq02Lh0004	pH	ph	0.059	0.24	222	7.80	6.10	7.01	1976	1988	6.98	7.03	7.02	7.18	7.16	7.07	7.03	6.92	6.86	7.03	6.89	7.07
Gatineau	Pq02Lh0004	PO4 ds.	mg/l	0.000	0.007	50	0.045	0.010	0.012	1985	1988	0.010	0.010	0.019	0.011	0.014	0.011	0.017	0.010	0.010	0.011	0.010	0.010
Gatineau	Pq02Lh0004	PO4 ds. ortho	mg/l			1	0.020	0.020	0.020	1976	1976												0.020

Tributary	Station no.	Variable	Unit	Var	StdDev	Cnt	Max	Min	Avg	First	Last	Year											
												Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Galineau	Pq02Lh0004	PO4 tot. inorg.	mg/l	0.000	0.014	67	0.13	0.020	0.023	1973	1976	0.020	0.020	0.075	0.023	0.027	0.020	0.022	0.020	0.020	0.020	0.020	
Galineau	Pq02Lh0004	Si react.	mg/l	1.03	1.02	282	8.30	0.50	3.82	1973	1985	3.55	3.93	4.26	5.01	4.34	3.60	3.38	3.23	3.15	3.53	3.84	
Galineau	Pq02Lh0004	SO4 dis.	mg/l	2.05	1.43	371	16	2.00	6.37	1973	1988	6.16	7.04	6.47	7.45	6.99	6.17	5.64	5.55	6.33	6.30	6.44	
Galineau	Pq02Lh0004	Sr tot.	mg/l	0.000	0.005	7	0.040	0.030	0.033	1982	1983		0.030	0.040				0.030	0.030				
Galineau	Pq02Lh0004	Temp.	deg c	69	8.32	486	27	0.000	10	1976	1988	0.47	0.12	0.21	4.09	11	18	21		13	5.23	0.84	
Kipawa	Pq02Le0002	Al ex.	mg/l	0.003	0.054	5	0.18	0.050	0.092	1982	1983		0.080		0.075			0.050		0.18			
Kipawa	Pq02Le0002	Alk tot. CaCO3	mg/l	3.16	1.78	61	14	0.90	2.87	1978	1986	2.02	4.07	2.80	3.20	2.36	3.04	2.78	3.42	2.48	2.52	3.15	
Kipawa	Pq02Le0002	C dis. inorg.	mg/l	0.013	0.12	3	0.60	0.40	0.47	1986	1986	0.40	0.60										
Kipawa	Pq02Le0002	C dis. org.	mg/l	0.040	0.20	3	4.40	4.00	4.20	1986	1986	4.10	4.40										
Kipawa	Pq02Le0002	C tot.	mg/l	11	3.31	132	30	4.00	8.59	1978	1983	8.72	8.25	9.23	8.41	8.00	7.15	9.88	10	7.50	9.55	8.63	
Kipawa	Pq02Le0002	C tot. inorg.	mg/l	3.72	1.93	132	22	0.50	0.95	1978	1983	0.78	1.00	0.86	0.86	0.68	0.55	0.75	0.61	0.60	0.78	1.31	
Kipawa	Pq02Le0002	Ca dis.	mg/l			1	3.10	3.10	3.10	1979	1979		3.10										
Kipawa	Pq02Le0002	Ca tot.	mg/l	0.086	0.29	62	3.80	2.00	2.73	1979	1986	2.60	3.00	2.88	3.00	2.73	2.58	2.50	2.74	2.60	2.70	2.70	
Kipawa	Pq02Le0002	Cl dis.	mg/l	0.47	0.69	70	5.00	0.20	0.81	1979	1986	0.68	0.94	0.65	1.11	0.74	0.53	0.78	1.26	0.68	0.67	0.80	
Kipawa	Pq02Le0002	Cond.	usiel/c	8.11	2.85	117	42	19	31	1978	1986	31	31	32	33	32	31	30	31	29	31	31	
Kipawa	Pq02Le0002	Fe ex.	mg/l	0.000	0.020	61	0.13	0.020	0.040	1980	1983	0.030	0.047	0.042	0.059	0.035	0.030	0.052	0.037	0.033	0.033	0.040	
Kipawa	Pq02Le0002	Fe tot.	mg/l	0.000	0.019	17	0.10	0.020	0.039	1979	1986	0.025	0.030	0.030	0.070	0.035	0.030	0.040	0.030	0.030	0.070		
Kipawa	Pq02Le0002	HCO3 calc.	mg/l	0.005	0.071	2	2.10	2.00	2.05	1986	1986	2.00	2.10										
Kipawa	Pq02Le0002	Hg ex.	ug/l	0.000	0.000	4	0.050	0.050	0.050	1979	1979		0.050		0.050				0.050				
Kipawa	Pq02Le0002	HN4 dis.	mg/l	0.000	0.013	78	0.080	0.010	0.025	1979	1983	0.025	0.025	0.027	0.032	0.020	0.024	0.020	0.028	0.020	0.020	0.020	
Kipawa	Pq02Le0002	K dis.	mg/l	0.050	0.22	35	1.80	0.58	0.75	1979	1983	0.70	0.70	0.90	0.85	0.72	0.60	0.70	0.65	0.64	1.80	0.70	
Kipawa	Pq02Le0002	Mg dis.	mg/l			1	0.70	0.70	0.70	1979	1979		0.70										
Kipawa	Pq02Le0002	Mg tot.	mg/l	0.008	0.091	76	1.00	0.60	0.76	1979	1983	0.74	0.72	0.76	0.84	0.79	0.77	0.80	0.74	0.72	0.75	0.80	
Kipawa	Pq02Le0002	Mn ex.	mg/l	0.000	0.006	61	0.030	0.010	0.012	1980	1983	0.010	0.010	0.010	0.010	0.013	0.010	0.010	0.015	0.014	0.017	0.017	
Kipawa	Pq02Le0002	Mn. tot.	mg/l	0.000	0.003	17	0.020	0.010	0.011	1979	1986	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.020		
Kipawa	Pq02Le0002	N dis.	mg/l	0.000	0.000	2	0.27	0.27	0.27	1986	1986	0.27	0.27										
Kipawa	Pq02Je0002	N dis. kjeld.	mg/l	0.001	0.038	43	0.25	0.090	0.16	1979	1983	0.18	0.14	0.11	0.18	0.13	0.16	0.18	0.16	0.14	0.15	0.17	
Kipawa	Pq02Je0002	N tot. kjeld.	mg/l	0.007	0.081	91	0.52	0.040	0.17	1978	1983	0.18	0.15	0.15	0.18	0.14	0.14	0.18	0.22	0.13	0.24	0.12	
Kipawa	Pq02Je0002	Na dis.	mg/l	0.043	0.21	35	1.70	0.70	0.99	1979	1983	1.10	0.92	1.10	1.13	1.02	0.83	0.90	1.00	0.88	1.00	1.40	
Kipawa	Pq02Je0002	NH4 tot.	mg/l	0.000	0.013	57	0.060	0.003	0.026	1978	1986	0.028	0.023	0.027	0.023	0.020	0.017	0.034	0.027	0.027	0.040	0.020	
Kipawa	Pq02Je0002	NO3 + NO2	mg/l	0.001	0.028	136	0.22	0.040	0.10	1978	1986	0.10	0.11	0.12	0.12	0.11	0.096	0.082	0.071	0.064	0.11	0.11	
Kipawa	Pq02Je0002	O2 dis.	mg/l	2.60	1.61	10	13	8.70	11	1979	1983		12		13	12				11			
Kipawa	Pq02Je0002	P dis. tot.	mg/l	0.000	0.006	87	0.033	0.006	0.010	1980	1983	0.009	0.014	0.008	0.013	0.011	0.007	0.013	0.007	0.008	0.008	0.008	
Kipawa	Pq02Je0002	P tot.	mg/l	0.000	0.003	4	0.006	0.000	0.003	1978	1986	0.000	0.000									0.006	

Appendix C

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kipawa	Pq02L0002	pH		0.13	0.36	67	7.30	5.50	6.23	1979	1986	6.16	6.28	6.03	6.22	5.95	6.20	6.30	6.58	6.23	6.22	6.15	6.23
Kipawa	Pq02L0002	PO4 dis.	mg/l	0.000	0.000	2	0.010	0.010	0.010	1986	1986	0.010	0.010										
Kipawa	Pq02L0002	Si react.	mg/l	1.05	1.02	34	3.70	0.20	1.46	1979	1982	0.73	1.22	2.00	1.52	1.70	1.30	2.30	2.05	0.95	1.37	0.75	3.70
Kipawa	Pq02L0002	SO4 dis.	mg/l	105	10	70	94	6.00	9.85	1979	1986	8.88	9.00	9.60	8.93	8.66	8.16	7.87	8.16	8.60	21	8.92	8.33
Kipawa	Pq02L0002	Si tot.	mg/l	0.000	0.006	3	0.040	0.030	0.033	1982	1983		0.030			0.030			0.040				
Kipawa	Pq02L0002	Temp.	deg c	46	6.77	193	25	0.000	10	1978	1986	3.20	3.66	4.35	5.22	7.70	14	21	21	16	11	6.92	4.22
Lievre	Pq02L0004	Al ex.	mg/l	0.007	0.085	13	0.33	0.050	0.11	1982	1985		0.060		0.24	0.11			0.057		0.060	0.11	
Lievre	Pq02L0004	Alk tot. CaCO3	mg/l	6.37	2.52	76	21	2.90	14	1976	1988	13	14	15	16	14	14	16	13	14	15	14	16
Lievre	Pq02L0004	C dis. inorg.	mg/l	0.40	0.64	87	5.30	0.60	3.57	1984	1988	3.69	3.84	4.08	4.33	3.11	3.13	3.64	3.21	3.73	3.64	3.27	3.37
Lievre	Pq02L0004	C dis. org.	mg/l	0.37	0.61	89	6.40	2.40	4.61	1984	1988	4.18	4.13	3.95	4.41	4.80	4.72	4.65	5.15	5.08	4.86	4.77	4.78
Lievre	Pq02L0004	C tot.	mg/l	58	7.59	107	77	7.00	13	1976	1983	11	12	22	12	11	12	13	12	11	12	14	19
Lievre	Pq02L0004	C tot. inorg.	mg/l	1.14	1.07	107	6.60	1.00	3.34	1976	1983	3.67	3.90	4.94	3.73	2.79	2.90	2.70	3.18	3.05	2.50	3.29	3.71
Lievre	Pq02L0004	Ca dis.	mg/l	0.020	0.14	2	6.00	5.80	5.90	1976	1979		5.80										
Lievre	Pq02L0004	Ca tot.	mg/l	1.64	1.28	273	15	1.50	5.96	1973	1988	5.84	6.22	6.92	7.30	5.52	5.25	5.97	5.88	5.81	5.35	5.67	6.30
Lievre	Pq02L0004	Cl dis.	mg/l	1.01	1.00	275	15	0.50	1.36	1973	1988	1.29	1.34	1.44	1.88	1.34	1.29	1.23	1.19	1.40	1.19	1.42	1.29
Lievre	Pq02L0004	Cond.	usie/c	531	23	369	450	14	50	1973	1988	48	52	56	58	43	45	48	48	45	44	60	51
Lievre	Pq02L0004	Fe ex.	mg/l	0.056	0.24	46	1.60	0.030	0.25	1980	1983	0.22	0.24	0.16	0.49	0.15	0.085	0.23	0.16	0.19	0.20	0.33	0.24
Lievre	Pq02L0004	Fe tot.	mg/l	0.019	0.14	77	0.82	0.12	0.26	1975	1988	0.24	0.22	0.23	0.45	0.21	0.17	0.25	0.25	0.17	0.28	0.29	0.29
Lievre	Pq02L0004	HCO3 calc.	mg/l	16	4.03	15	21	3.50	16	1986	1987	16	18	18	18	14	15	20	3.50	21	20	17	18
Lievre	Pq02L0004	Hg ex.	ug/l	0.000	0.000	7	0.050	0.050	0.050	1976	1979		0.050		0.050					0.050	0.050	0.050	
Lievre	Pq02L0004	HN4 dis.	mg/l	0.000	0.015	75	0.080	0.010	0.031	1976	1983	0.030	0.037	0.025	0.037	0.033	0.023	0.022	0.033	0.024	0.032	0.031	0.037
Lievre	Pq02L0004	K dis.	mg/l	0.044	0.21	202	2.00	0.30	0.72	1973	1983	0.60	0.66	0.69	0.81	0.66	0.71	0.74	0.84	0.73	0.65	0.77	0.68
Lievre	Pq02L0004	Mg dis.	mg/l	0.005	0.071	2	1.00	0.90	0.95	1976	1979		0.90									1.00	
Lievre	Pq02L0004	Mg tot.	mg/l	0.12	0.34	226	4.20	0.10	0.96	1973	1983	0.85	0.99	1.06	1.14	0.86	0.79	0.92	1.04	1.04	0.79	1.01	0.99
Lievre	Pq02L0004	Mn ex.	mg/l	0.000	0.009	50	0.050	0.010	0.018	1980	1984	0.020	0.011	0.015	0.025	0.014	0.012	0.015	0.012	0.018	0.023	0.026	0.025
Lievre	Pq02L0004	Mn tot.	mg/l	0.000	0.009	77	0.050	0.010	0.021	1975	1988	0.017	0.012	0.015	0.029	0.020	0.020	0.027	0.024	0.018	0.021	0.017	0.020
Lievre	Pq02L0004	N dis.	mg/l	0.007	0.082	54	0.63	0.20	0.33	1985	1988	0.32	0.36	0.37	0.49	0.35	0.32	0.31	0.26	0.27	0.28	0.32	0.37
Lievre	Pq02L0004	N dis. kjeld.	mg/l	0.002	0.050	45	0.35	0.11	0.19	1976	1983	0.22	0.15	0.18	0.16	0.20	0.21	0.17	0.23	0.23	0.16	0.16	0.24
Lievre	Pq02L0004	N tot. kjeld.	mg/l	0.75	0.87	96	6.80	0.10	0.39	1978	1985	0.19	0.20	1.04	0.17	0.18	0.34	0.52	0.43	0.20	0.19	0.46	0.64
Lievre	Pq02L0004	Na dis.	mg/l	1.72	1.31	202	19	0.60	1.32	1973	1983	1.21	1.60	1.29	1.39	1.02	1.10	1.23	2.06	1.23	1.04	1.17	1.30
Lievre	Pq02L0004	NH4 tot.	mg/l	0.36	0.60	120	4.60	0.002	0.15	1978	1988	0.026	0.037	0.49	0.022	0.025	0.031	0.24	0.21	0.037	0.029	0.24	0.26
Lievre	Pq02L0004	NO3 + NO2	mg/l	0.18	0.43	347	7.00	0.020	0.25	1973	1988	0.33	0.22	0.58	0.33	0.29	0.20	0.18	0.16	0.15	0.17	0.24	0.29
Lievre	Pq02L0004	O2 dis.	mg/l	4.02	2.00	21	15	7.70	12	1976	1985		13		13	12			8.87	8.30	11	12	
Lievre	Pq02L0004	P dis. tot.	mg/l	0.002	0.046	99	0.41	0.006	0.023	1979	1985	0.017	0.028	0.063	0.017	0.011	0.043	0.027	0.010	0.015	0.011	0.010	0.043

Appendix C

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StdDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lievre	Pq02L0004	P susp.	ug/l	0.000	0.011	71	0.069	0.000	0.004	1984	1988	0.003	0.009	0.002	0.006	0.006	0.008	0.003	0.003	0.004	0.002	0.003	0.003
Lievre	Pq02L0004	P tot.	mg/l	0.000	0.022	27	0.090	0.000	0.022	1976	1987	0.056	0.021	0.038	0.065	0.038	0.034	0.011	0.007	0.010	0.011	0.028	0.014
Lievre	Pq02L0004	pH	ph	0.15	0.38	119	7.80	4.00	7.02	1976	1988	7.15	7.00	7.02	7.16	7.16	7.03	6.66	6.85	7.06	7.15	6.94	7.00
Lievre	Pq02L0004	PO4 dis.	mg/l	0.001	0.030	54	0.21	0.010	0.018	1985	1988	0.012	0.062	0.015	0.016	0.012	0.011	0.031	0.013	0.012	0.010	0.013	0.011
Lievre	Pq02L0004	PO4 dis. ortho	mg/l		1		0.020	0.020	0.020	1976	1976											0.020	
Lievre	Pq02L0004	PO4 tot. inorg.	mg/l	0.001	0.024	55	0.17	0.020	0.028	1973	1976	0.030	0.027	0.050	0.055	0.020	0.021	0.033	0.028	0.020	0.022	0.020	0.020
Lievre	Pq02L0004	Si react.	mg/l	1.09	1.05	208	7.20	0.10	3.55	1973	1985	3.91	4.40	4.35	3.98	3.04	2.95	3.21	3.11	3.21	3.51	3.57	3.91
Lievre	Pq02L0004	SO4 dis.	mg/l	1.89	1.37	278	16	1.00	6.23	1973	1988	6.60	6.54	6.56	7.86	5.99	5.72	5.61	5.45	5.80	5.81	6.60	6.62
Lievre	Pq02L0004	Si tot.	mg/l	0.000	0.012	3	0.050	0.030	0.037	1982	1983		0.030		0.050				0.030				
Lievre	Pq02L0004	Temp.	deg c	66	8.13	296	25	0.000	11	1976	1988	1.08	0.89	1.06	4.46	11	18	22	21	18	12	5.20	1.28
Madawaska	On02Ke0002	Alk tot. CaCO3	mg/l	342	18	116	216	4.00	44	1971	1984	41	41	35	45	43	43	44	67	42	46	45	39
Madawaska	On02Ke0002	BOD	mg/l	0.68	0.82	72	5.00	0.20	0.93	1971	1981	1.54	0.80	0.83	1.16	0.90	0.80	0.60	1.37	0.63	0.64	1.16	0.50
Madawaska	On02Ke0002	Cl dis.	mg/l	271	16	79	148	1.00	4.29	1971	1984	3.01	2.36	2.17	2.26	2.63	2.12	1.77	3.89	1.66	2.06	27	2.63
Madawaska	On02Ke0002	Cond.	usie/c	1198	35	116	460	87	117	1971	1984	109	103	105	117	114	116	124	155	119	118	113	106
Madawaska	On02Ke0002	Fe tot.	mg/l	0.14	0.38	100	2.70	0.080	0.31	1971	1984	0.28	0.54	0.40	0.37	0.58	0.28	0.22	0.26	0.22	0.20	0.23	0.15
Madawaska	On02Ke0002	Hg tot.	ug/l	0.17	0.41	14	1.20	0.010	0.18	1977	1984		0.060	0.010	0.020	0.010	0.010	0.010	0.030	0.015	0.38	0.62	
Madawaska	On02Ke0002	HN4 dis.	mg/l	0.000	0.014	104	0.060	0.002	0.017	1971	1984	0.011	0.030	0.019	0.010	0.015	0.012	0.019	0.018	0.028	0.017	0.013	0.014
Madawaska	On02Ke0002	Mg tot.	mg/l	21	4.61	74	42	1.00	3.38	1971	1984	2.86	2.47	2.94	2.71	2.75	9.58	2.70	2.92	2.74	2.75	3.20	3.47
Madawaska	On02Ke0002	Mn. tot.	mg/l	0.000	0.015	67	0.080	0.014	0.034	1971	1984	0.036	0.027	0.026	0.035	0.036	0.031	0.037	0.044	0.035	0.033	0.035	0.023
Madawaska	On02Ke0002	N tot.	mg/l	0.25	0.50	73	3.89	0.17	0.47	1971	1984	0.75	0.38	0.94	0.42	0.44	0.42	0.35	0.36	0.33	0.34	0.34	0.42
Madawaska	On02Ke0002	N tot. kjeld.	mg/l	0.077	0.28	160	2.70	0.11	0.33	1971	1984	0.64	0.22	0.26	0.28	0.36	0.35	0.31	0.33	0.30	0.30	0.30	0.33
Madawaska	On02Ke0002	NO3 dis.	mg/l	0.17	0.41	78	3.63	0.005	0.11	1971	1984	0.099	0.14	0.66	0.13	0.085	0.049	0.026	0.014	0.011	0.020	0.029	0.041
Madawaska	On02Ke0002	NO3 dis.	mg/l	0.000	0.003	80	0.019	0.001	0.004	1971	1984	0.003	0.003	0.006	0.005	0.005	0.005	0.004	0.003	0.003	0.004	0.002	0.003
Madawaska	On02Ke0002	O2 dis.	mg/l	4.28	2.07	118	20	5.50	11	1971	1984	13	12	13	13	10	9.71	8.59	8.69	9.20	9.74	11	12
Madawaska	On02Ke0002	P tot.	mg/l	0.000	0.021	121	0.13	0.004	0.023	1971	1984	0.015	0.030	0.021	0.017	0.027	0.024	0.032	0.029	0.021	0.020	0.018	0.019
Madawaska	On02Ke0002	pH	ph	0.062	0.25	117	8.40	7.10	7.68	1971	1984	7.59	7.52	7.56	7.56	7.80	7.66	7.56	7.76	7.80	7.76	7.74	7.73
Madawaska	On02Ke0002	PO4 dis.	mg/l	0.000	0.012	84	0.078	0.001	0.007	1971	1981	0.004	0.017	0.007	0.003	0.005	0.015	0.003	0.008	0.005	0.004	0.006	0.004
Madawaska	On02Ke0002	Temp.	deg c	69	8.30	120	24	0.000	11	1971	1984	0.77	0.77	1.53	6.12	12	18	21	21	20	12	5.09	1.44
Mattawa	On02Je0014	Alk tot. CaCO3	mg/l	11	3.35	38	23	9.10	15	1971	1984	17		16	13	11	14	18	16	19	16	17	15
Mattawa	On02Je0014	BOD	mg/l	0.72	0.85	82	4.00	0.20	1.18	1971	1979	1.13	0.96	1.22	1.19	1.11	1.48	1.20	1.60	1.29	0.75	1.23	0.96
Mattawa	On02Je0014	Cl dis.	mg/l	2.27	1.51	131	16	1.00	2.26	1971	1984	2.33	2.59	3.58	2.18	2.05	2.79	1.96	1.86	2.53	1.91	1.87	2.16
Mattawa	On02Je0014	Cond.	usie/c	214	15	135	144	41	63	1971	1984	58	64	63	65	58	63	61	61	66	62	69	63
Mattawa	On02Je0014	daily av. dsch.	m3/s	1290	36	8	110	4.28	25	1971	1971			18		72	21	4.28	4.56	4.59	6.40		
Mattawa	On02Je0014	Fe tot.	mg/l	0.011	0.11	41	0.55	0.050	0.25	1971	1984	0.30		0.21	0.33	0.16	0.28	0.27	0.19	0.25	0.19	0.28	0.30

Appendix C

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StdDev	Crit	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mattawa	On02Je0014	Hg tot.	ug/l	0.000	0.000	3	0.010	0.010	0.010	1984	1984	0.044	0.067	0.029	0.036	0.048	0.061	0.11	0.12	0.13	0.010	0.010	0.010
Mattawa	On02Je0014	HN4 ds.	mg/l	0.005	0.072	135	0.35	0.002	0.081	1971	1984										0.12	0.096	0.083
Mattawa	On02Je0014	Mg tot.	mg/l	0.000	0.000	2	1.72	1.72	1.72	1984	1984										1.72	1.72	
Mattawa	On02Je0014	Mn. tot.	mg/l	0.000	0.000	2	0.018	0.018	0.018	1984	1984										0.018	0.018	
Mattawa	On02Je0014	N tot.	mg/l	0.10	0.32	102	2.86	0.28	0.62	1971	1982	0.86	0.52	0.59	0.52	0.53	0.65	0.67	0.64	0.68	0.65	0.57	0.58
Mattawa	On02Je0014	N tot. kjeld	mg/l	0.087	0.30	226	2.70	0.10	0.45	1971	1984	0.72	0.30	0.34	0.33	0.38	0.50	0.53	0.51	0.52	0.44	0.37	0.48
Mattawa	On02Je0014	NO3 ds.	mg/l	0.005	0.069	104	0.38	0.010	0.12	1971	1984	0.11	0.19	0.24	0.17	0.13	0.099	0.075	0.065	0.089	0.12	0.12	0.14
Mattawa	On02Je0014	NO3 ds.	mg/l	0.000	0.002	103	0.011	0.002	0.004	1971	1984	0.004	0.003	0.004	0.005	0.005	0.005	0.004	0.005	0.005	0.005	0.004	0.004
Mattawa	On02Je0014	O2 ds.	mg/l	4.60	2.14	110	14	3.00	9.01	1971	1984	10	11	11	11	9.64	8.43	8.29	7.84	7.69	8.93	8.76	9.10
Mattawa	On02Je0014	P tot.	mg/l	0.001	0.036	137	0.30	0.003	0.026	1971	1984	0.024	0.011	0.015	0.017	0.044	0.028	0.036	0.020	0.039	0.021	0.029	0.016
Mattawa	On02Je0014	pH	ph	0.057	0.24	49	7.46	6.43	7.09	1971	1984	7.20		6.96	6.96	7.07	7.12	7.21	7.12	7.05	6.94	7.19	7.29
Mattawa	On02Je0014	PO4 ds.	mg/l	0.001	0.027	107	0.24	0.001	0.007	1971	1981	0.003	0.003	0.003	0.002	0.025	0.004	0.002	0.006	0.002	0.003	0.018	0.003
Mattawa	On02Je0014	Temp.	deg c	69	8.29	135	25	0.000	11	1971	1984	0.90	0.60	1.46	4.12	11	20	22	22	18	9.46	6.07	1.45
Mississippi	On02Kf0002	Al ex.	mg/l	0.002	0.049	9	0.14	0.000	0.024	1970	1971	0.050		0.000		0.000	0.000	0.070	0.000		0.000		
Mississippi	On02Kf0002	Alk tot. CaCO3	mg/l	285	17	89	117	7.00	93	1970	1984	102	100	86	86	84	97	94	97	80	103	96	98
Mississippi	On02Kf0002	BOD	mg/l	1.06	1.03	63	6.50	0.20	1.35	1970	1979	1.90	0.93	1.70	1.25	1.54	1.67	0.80	0.86	1.20	1.52	0.97	1.00
Mississippi	On02Kf0002	Ca tot.	mg/l	51	7.13	17	40	13	32	1970	1971	38	38	29	29	26	32	32	34		32		
Mississippi	On02Kf0002	Cl ds.	mg/l	15	3.81	70	34	2.00	5.84	1970	1984	5.50	6.00	6.68	7.00	4.04	4.43	4.37	5.10	4.89	6.24	9.57	6.98
Mississippi	On02Kf0002	Cond.	usie/c	479	22	114	280	175	220	1970	1984	240	236	226	257	199	218	215	211	203	234	224	240
Mississippi	On02Kf0002	Fe ex.	mg/l	0.30	0.55	14	2.30	0.15	0.42	1970	1971	0.20	0.18	0.30	2.30	0.45	0.25	0.15	0.25	0.40	0.30		
Mississippi	On02Kf0002	Fe tot.	mg/l	0.13	0.36	69	2.50	0.10	0.30	1972	1984	0.17	0.21	0.70		0.31	0.24	0.21	0.21	0.22	0.26	0.24	0.18
Mississippi	On02Kf0002	Hg tot.	ug/l	0.34	0.58	7	1.30	0.010	0.35	1984	1984			0.010		0.020	0.010	0.010	0.010	0.010	1.10	1.30	
Mississippi	On02Kf0002	HN4 ds.	mg/l	0.001	0.037	91	0.20	0.002	0.039	1972	1984	0.074	0.018	0.066	0.085	0.017	0.028	0.033	0.042	0.027	0.027	0.035	0.024
Mississippi	On02Kf0002	K ds.	mg/l	0.068	0.26	16	2.00	1.00	1.42	1970	1971	1.60	1.45	1.47	2.00	1.30	1.40		1.05		1.20		
Mississippi	On02Kf0002	Mg ds.	mg/l	3.03	1.74	17	8.00	2.00	5.82	1970	1971	7.33	6.50	5.33	7.00	5.00	6.00	5.00	4.50		6.00		
Mississippi	On02Kf0002	Mg tot.	mg/l	3.63	1.91	35	14	5.00	7.08	1972	1984	8.20	5.30	8.31		6.01		6.26	7.00	7.63	6.75	6.78	6.10
Mississippi	On02Kf0002	Mn ex.	mg/l	0.000	0.000	7	0.010	0.010	0.010	1970	1971	0.010			0.010			0.010	0.010		0.010		
Mississippi	On02Kf0002	Mn. tot.	mg/l	0.001	0.023	33	0.13	0.010	0.039	1972	1984	0.032		0.053		0.048	0.029	0.039		0.032	0.031	0.036	0.016
Mississippi	On02Kf0002	N tot.	mg/l	0.21	0.46	51	2.89	0.33	0.70	1972	1984	0.94	0.53	1.22	1.07	0.47	0.56	0.49	0.52	0.65	0.74	0.50	0.65
Mississippi	On02Kf0002	N tot. kjeld.	mg/l	0.062	0.25	140	1.80	0.11	0.53	1970	1984	0.77	0.41	0.54	0.66	0.46	0.51	0.47	0.48	0.57	0.56	0.40	0.42
Mississippi	On02Kf0002	Na ds.	mg/l	0.57	0.76	15	4.00	2.00	3.00	1970	1971	2.67	3.50	3.33	3.00	2.67	3.00		3.00				
Mississippi	On02Kf0002	NH4 tot.	mg/l	0.001	0.037	18	0.15	0.010	0.062	1970	1971	0.070	0.080	0.050	0.13	0.050	0.15	0.060	0.050	0.010	0.030	0.030	
Mississippi	On02Kf0002	NO3 + NO2	mg/l	0.008	0.092	17	0.30	0.010	0.10	1970	1971	0.073	0.11	0.22	0.29	0.090		0.010	0.010	0.060	0.020	0.020	
Mississippi	On02Kf0002	NO3 ds.	mg/l	0.11	0.34	58	2.49	0.005	0.14	1972	1984	0.14	0.13	0.60	0.38	0.025	0.057	0.018	0.017	0.017	0.040	0.071	0.21

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mississippi	On02Kf0002	NO3 dis.	mg/l	0.000	0.010	80	0.058	0.000	0.007	1970	1984	0.005	0.019	0.007	0.026	0.006	0.005	0.003	0.002	0.009	0.002	0.004	0.006
Mississippi	On02Kf0002	O2 dis.	mg/l	8.20	2.86	156	20	0.90	9.47	1970	1984	10	10	10	10	8.49	8.79	7.88	8.08	8.50	8.91	11	11
Mississippi	On02Kf0002	P tot.	mg/l	0.006	0.079	111	0.78	0.005	0.041	1970	1984	0.034	0.018	0.045	0.079	0.028	0.031	0.035	0.033	0.090	0.053	0.025	0.019
Mississippi	On02Kf0002	pH	ph	0.045	0.21	88	8.40	7.40	7.98	1970	1984	7.80	7.91	7.77	8.00	8.05	8.05	8.09	8.12	8.04	8.02	7.96	8.13
Mississippi	On02Kf0002	PO4 dis.	mg/l	0.000	0.008	53	0.036	0.001	0.011	1972	1980	0.009	0.007	0.018	0.023	0.005	0.005	0.014	0.015	0.009	0.012	0.012	0.002
Mississippi	On02Kf0002	PO4 dis. ortho	mg/l	0.000	0.003	20	0.016	0.002	0.004	1970	1971	0.003	0.003	0.003	0.016	0.002	0.002	0.002	0.006	0.003	0.003	0.003	0.003
Mississippi	On02Kf0002	Si react.	mg/l	2.84	1.68	17	7.10	1.60	4.57	1970	1971	5.47	6.40	6.17	5.30	3.93	2.90	2.60	2.45	2.60	2.60	14	14
Mississippi	On02Kf0002	SO4 dis.	mg/l	9.18	3.03	18	18	7.00	14	1970	1971	16	15	15	7.00	14	16	8.00	15	19	9.19	3.89	0.38
Mississippi	On02Kf0002	Temp.	deg c	91	9.55	159	28	0.000	10	1970	1984	0.12	0.12	1.05	3.13	13	21	23	24	19	26	27	19
Nord	Pq02Lc0002	Alk tot. CaCO3	mg/l	129	11	81	84	3.00	27	1976	1988	30	39	28	15	26	23	27	30	27	26	27	19
Nord	Pq02Lc0002	BOD	mg/l	1.31	1.14	6	3.50	0.20	1.53	1976	1978							1.27	1.80				
Nord	Pq02Lc0002	C dis. inorg.	mg/l	3.01	1.73	16	12	4.20	8.21	1986	1988	8.20	8.40	8.60	4.20	7.90	7.70		11	7.10	8.30		
Nord	Pq02Lc0002	C dis. org.	mg/l	0.93	0.97	18	6.30	2.90	4.25	1986	1988	4.17	3.50	3.70	3.70	3.10	4.20		4.95	5.80	4.70		
Nord	Pq02Lc0002	C tot.	mg/l	11	3.36	85	23	6.00	15	1976	1979	16	16	16	11	12	16	16	18	17	16	16	16
Nord	Pq02Lc0002	C tot. inorg.	mg/l	3.49	1.87	84	9.00	1.00	4.93	1976	1979	6.33	7.29	6.30	3.64	4.06	4.42	5.50	5.25	4.00	4.81	4.50	4.75
Nord	Pq02Lc0002	Ca dis.	mg/l	4.26	2.06	27	14	6.50	11	1976	1979	11	12	13	6.50	9.10	12	9.77	10	12	10	11	11
Nord	Pq02Lc0002	Ca tot.	mg/l	11	3.36	83	26	4.00	11	1972	1988	12	12	12	9.81	11	9.58	11	12	13	12	9.83	9.85
Nord	Pq02Lc0002	Cl dis.	mg/l	102	10	101	52	1.70	22	1972	1988	27	27	35	11	15	20	23	26	23	19	18	14
Nord	Pq02Lc0002	Cond.	usiel/c	2246	47	146	278	20	153	1972	1988	183	170	190	113	120	152	155	167	166	143	139	129
Nord	Pq02Lc0002	Fe tot.	mg/l	0.099	0.31	91	2.10	0.13	0.50	1972	1988	0.36	0.37	0.37	0.90	0.40	0.39	0.39	0.42	0.62	0.57	0.55	0.41
Nord	Pq02Lc0002	HCO3 calc.	mg/l	45	6.73	11	45	21	36	1972	1987	39	38	39	21				0.42	32	38		
Nord	Pq02Lc0002	Hg ex.	ug/l	0.20	0.45	44	3.06	0.050	0.16	1976	1979	0.095	0.053	0.16	0.14	0.60	0.13	0.063	0.11	0.050	0.077	0.050	0.050
Nord	Pq02Lc0002	HN4 dis.	mg/l	0.010	0.100	52	0.47	0.010	0.097	1976	1979	0.18	0.28	0.24	0.070	0.047	0.098	0.060	0.057	0.067	0.044	0.050	0.065
Nord	Pq02Lc0002	K dis.	mg/l	0.20	0.45	75	2.70	0.10	0.98	1972	1979	0.95	0.98	0.84	0.95	0.64	0.87	1.07	1.18	1.63	1.12	0.78	0.82
Nord	Pq02Lc0002	Mg dis.	mg/l	0.37	0.61	27	3.70	1.00	2.64	1976	1979	2.60	2.93	2.85	2.10	2.05	2.75	2.75	2.65	2.65	2.70	3.05	2.80
Nord	Pq02Lc0002	Mg tot.	mg/l	0.50	0.71	66	4.50	0.90	2.59	1972	1979	3.04	2.96	2.63	2.05	2.03	2.12	2.62	2.58	3.34	2.72	2.70	2.25
Nord	Pq02Lc0002	Mn. tot.	mg/l	0.000	0.016	91	0.080	0.010	0.044	1972	1988	0.035	0.041	0.048	0.055	0.037	0.063	0.053	0.043	0.041	0.031	0.037	0.043
Nord	Pq02Lc0002	N dis.	mg/l	0.042	0.20	16	1.24	0.53	0.90	1986	1988	0.98	1.10	1.09	0.76	0.64	0.98		0.64	0.80	0.84		
Nord	Pq02Lc0002	N dis. kjeld.	mg/l	0.026	0.16	52	0.95	0.10	0.37	1976	1979	0.43	0.48	0.52	0.32	0.24	0.42	0.34	0.36	0.48	0.39	0.29	0.31
Nord	Pq02Lc0002	N tot. kjeld.	mg/l	0.010	0.10	32	0.69	0.15	0.35	1976	1979	0.44	0.51	0.33	0.19	0.26	0.30	0.40	0.36	0.36	0.37	0.34	0.34
Nord	Pq02Lc0002	Na dis.	mg/l	31	5.60	75	31	0.80	13	1972	1979	15	14	19	7.85	8.79	12	13	12	18	13	12	10
Nord	Pq02Lc0002	NH4 tot.	mg/l	0.004	0.062	47	0.25	0.007	0.084	1976	1988	0.14	0.11	0.13	0.033	0.050	0.077	0.13	0.053	0.074	0.064	0.085	0.087
Nord	Pq02Lc0002	NO3 + NO2	mg/l	0.47	0.69	139	4.00	0.10	0.64	1972	1988	1.22	0.95	0.74	0.49	0.31	0.57	0.63	0.60	0.76	0.28	0.55	0.59
Nord	Pq02Lc0002	O2 dis.	mg/l	7.11	2.67	52	18	6.30	11	1976	1979	13	14	15	14	10	8.64	8.08	8.50	8.60	12	13	13

Appendix C

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nord	Pq02Lc0002	P susp.	ugl	0.000	0.011	8	0.068	0.038	0.049	1987	1988			0.051	0.056	0.046	0.056		0.054	0.038	0.040		
Nord	Pq02Lc0002	P tot.	mg/l	0.005	0.068	27	0.31	0.013	0.072	1976	1987	0.18		0.084	0.041	0.013	0.056	0.062	0.060	0.047	0.052	0.088	0.040
Nord	Pq02Lc0002	pH	ph	0.14	0.38	73	8.30	5.80	7.27	1972	1988	7.15	6.98	7.40	7.17	7.36	7.62	7.30	7.41	7.22	7.11	7.40	7.15
Nord	Pq02Lc0002	PO4 dis.	mg/l	0.000	0.015	16	0.070	0.010	0.036	1986	1988	0.035	0.043	0.018	0.025	0.025	0.030		0.058	0.038	0.038		
Nord	Pq02Lc0002	PO4 dis. ortho	mg/l	0.000	0.012	14	0.042	0.007	0.018	1976	1977	0.027	0.042				0.007	0.013	0.021	0.016	0.013	0.020	0.007
Nord	Pq02Lc0002	PO4 tot. inorg.	mg/l	0.010	0.100	40	0.50	0.000	0.092	1972	1976	0.053	0.064	0.17	0.34	0.059	0.10	0.067	0.080	0.073	0.070	0.057	0.063
Nord	Pq02Lc0002	Si react.	mg/l	3.11	1.76	88	8.50	0.60	5.05	1972	1979	5.98	6.93	7.34	3.96	2.86	4.50	3.76	4.96	4.64	5.27	5.69	5.36
Nord	Pq02Lc0002	SO4 dis.	mg/l	111	11	105	115	0.80	12	1972	1988	13	12	25	9.46	9.40	8.89	9.20	12	12	11	12	10
Nord	Pq02Lc0002	Temp.	deg c	68	8.25	108	25	0.10	11	1976	1988	1.17	1.00	1.30	5.09	12	21	23	21	16	8.31	4.61	1.03
Pelawawa	On02Kb0001	Al ex.	mg/l	0.004	0.061	7	0.15	0.000	0.074	1970	1971	0.070			0.12	0.000		0.080			0.030	0.15	
Pelawawa	On02Kb0001	Alk tot. CaCO3	mg/l	783	28	97	241	6.10	18	1970	1984	23	13	16	12	10	11	14	13	14	20	59	19
Pelawawa	On02Kb0001	BOD	mg/l	0.83	0.91	72	7.00	0.20	0.93	1970	1980	1.17	1.09	0.91	1.10	0.67	0.80	1.50	0.64	0.64	0.74	0.85	0.90
Pelawawa	On02Kb0001	Ca tot.	mg/l	160	13	18	59	1.00	8.61	1970	1971	7.00	6.00	5.50	6.00	23	5.00	6.00	3.50		6.00	6.00	
Pelawawa	On02Kb0001	Cl dis.	mg/l	8.72	2.95	73	26	0.50	1.65	1970	1984	1.83	1.63	1.13	1.35	1.36	5.41	1.40	1.12	1.04	1.13	1.44	0.80
Pelawawa	On02Kb0001	Cond.	usielc	257	16	107	158	42	53	1970	1984	51	52	63	49	47	48	59	48	52	49	59	65
Pelawawa	On02Kb0001	daily av. disch.	m3/s	3488	59	69	263	7.48	63	1971	1981	32	28	59	183	131	80	39	37	38	51	56	32
Pelawawa	On02Kb0001	Fe ex.	mg/l	0.006	0.078	9	0.40	0.10	0.21	1970	1971	0.20	0.20		0.21	0.40	0.20	0.20	0.13	0.17	0.19	0.19	0.14
Pelawawa	On02Kb0001	Fe tot.	mg/l	0.009	0.093	78	0.77	0.050	0.21	1972	1984	0.22	0.25	0.24	0.23	0.30	0.23	0.20	0.20		0.40	0.010	0.010
Pelawawa	On02Kb0001	Hg tot.	ugl	0.001	0.024	13	0.080	0.010	0.030	1979	1984	0.030		0.070	0.025	0.080	0.010	0.019	0.017	0.017	0.011	0.021	0.014
Pelawawa	On02Kb0001	HN4 dis.	mg/l	0.000	0.012	90	0.076	0.001	0.017	1971	1984	0.021	0.014	0.017	0.014	0.015	0.026		0.017				
Pelawawa	On02Kb0001	K dis.	mg/l	0.008	0.089	16	0.90	0.60	0.76	1970	1971	0.80	0.80	0.80	0.80	0.65	0.80	1.00	0.75		0.77	0.60	
Pelawawa	On02Kb0001	Mg dis.	mg/l	5.43	2.33	18	11	1.00	1.56	1971	1984	1.50	1.50	1.50	1.40	4.33	1.00	1.00	2.00		1.67	1.00	1.93
Pelawawa	On02Kb0001	Mg tot.	mg/l	0.56	0.76	47	4.00	0.55	1.56	1971	1984	1.00	1.64	1.92	1.39	1.00	1.91	1.56	1.74	1.38	1.32	1.64	
Pelawawa	On02Kb0001	Mn ex.	mg/l	0.000	0.010	7	0.030	0.010	0.016	1970	1971	0.010			0.010	0.030		0.010			0.010	0.030	
Pelawawa	On02Kb0001	Mn. tot.	mg/l	0.003	0.050	40	0.34	0.011	0.043	1972	1984	0.12	0.031	0.033	0.043	0.040	0.029	0.040	0.030	0.040	0.037	0.026	0.025
Pelawawa	On02Kb0001	N tot.	mg/l	0.075	0.27	60	2.18	0.17	0.40	1971	1984	0.85	0.44	0.47	0.37	0.32	0.37	0.36	0.30	0.29	0.32	0.34	0.30
Pelawawa	On02Kb0001	N tot. kjeld.	mg/l	0.058	0.24	143	2.10	0.13	0.31	1970	1984	0.69	0.23	0.29	0.25	0.27	0.30	0.33	0.28	0.25	0.30	0.25	0.24
Pelawawa	On02Kb0001	Na dis.	mg/l	10	3.22	15	14	1.00	2.60	1970	1971	1.00	3.00	2.00	2.00	7.50	2.00	0.12	1.50		1.67	1.00	
Pelawawa	On02Kb0001	NH4 tot.	mg/l	0.002	0.042	15	0.12	0.010	0.045	1970	1971	0.060	0.030	0.010	0.020	0.027	0.15		0.12		0.065	0.010	
Pelawawa	On02Kb0001	NO3 + NO2	mg/l	0.002	0.045	15	0.16	0.010	0.082	1970	1971	0.070	0.11	0.11	0.10	0.070	0.15		0.12		0.017	0.16	
Pelawawa	On02Kb0001	NO3 dis.	mg/l	0.008	0.087	65	0.60	0.005	0.078	1971	1984	0.094	0.21	0.17	0.11	0.063	0.067	0.020	0.018	0.023	0.038	0.10	0.061
Pelawawa	On02Kb0001	NO3 dis.	mg/l	0.000	0.002	82	0.010	0.000	0.003	1970	1984	0.002	0.003	0.002	0.003	0.002	0.004	0.002	0.003	0.003	0.002	0.002	0.004
Pelawawa	On02Kb0001	O2 dis.	mg/l	5.69	2.38	104	15	3.90	9.67	1970	1984	11	11	11	10	9.51	8.19	7.54	9.29	8.06	9.59	11	12
Pelawawa	On02Kb0001	P tot.	mg/l	0.12	0.35	107	3.60	0.001	0.047	1970	1984	0.010	0.013	0.009	0.022	0.023	0.018	0.011	0.41	0.011	0.011	0.011	0.009

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StDev	Crit	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pelawawa	On02Kb0001	pH	ph	0.19	0.43	98	9.54	6.40	7.35	1970	1984	7.27	7.30	7.26	7.14	7.22	7.04	7.36	7.47	7.52	7.43	7.68	7.92
Pelawawa	On02Kb0001	PO4 dis.	mg/l	0.000	0.003	58	0.018	0.001	0.003	1971	1981	0.005	0.003	0.002	0.002	0.006	0.003	0.002	0.005	0.002	0.003	0.003	0.002
Pelawawa	On02Kb0001	PO4 dis. ortho	mg/l	0.000	0.012	18	0.055	0.002	0.005	1970	1971	0.002	0.002	0.002	0.002	0.002	0.055	0.002	0.002	0.002	0.002	0.002	0.002
Pelawawa	On02Kb0001	Si react.	mg/l	1.50	1.23	16	6.70	2.00	4.36	1970	1971	4.85	3.50	5.85	5.80	5.15	2.30	3.50	3.80	3.80	3.93		
Pelawawa	On02Kb0001	SO4 dis.	mg/l	7.83	2.80	18	17	7.00	11	1970	1971	8.50	10	10	7.00	12	11	7.00	14	19	13	10	
Pelawawa	On02Kb0001	Temp.	deg c	77	8.78	106	30	0.000	10	1970	1984	0.93	0.97	2.00	5.54	12	18	23	21	21	10	4.72	3.00
Petite Nation	Pq02Ld0001	Al ex.	mg/l	0.091	0.30	13	1.18	0.090	0.28	1982	1985		0.12		0.40	0.11			0.15		0.14	0.67	
Petite Nation	Pq02Ld0001	Alk tot. CaCO3	mg/l	129	11	87	96	0.000	24	1971	1988	33	22	27	21	16	20	23	25	25	29	23	21
Petite Nation	Pq02Ld0001	C dis. inorg.	mg/l	11	3.34	69	24	3.20	5.69	1984	1988	10	5.33	5.00	3.72	3.68	4.36	5.13	5.20	5.38	6.37	6.41	5.58
Petite Nation	Pq02Ld0001	C dis. org.	mg/l	19	4.36	71	36	3.10	5.22	1984	1988	7.49	8.50	4.80	4.34	3.63	4.20	5.04	4.30	4.55	4.53	4.90	5.13
Petite Nation	Pq02Ld0001	C tot.	mg/l	30	5.50	114	60	7.00	14	1976	1983	12	17	13	12	12	13	14	16	17	16	14	17
Petite Nation	Pq02Ld0001	C tot. inorg.	mg/l	8.71	2.95	114	31	1.00	5.16	1976	1983	4.29	7.18	5.06	3.85	3.44	4.36	5.43	6.17	6.46	5.64	4.43	5.25
Petite Nation	Pq02Ld0001	Ca dis.	mg/l	0.25	0.49	2	10	9.40	9.75	1976	1979		9.40										
Petite Nation	Pq02Ld0001	Ca tot.	mg/l	10	3.24	104	37	6.00	10	1971	1988	9.10	9.49	10	7.50	7.69	8.54	9.77	11	13	12	11	9.72
Petite Nation	Pq02Ld0001	Cl dis.	mg/l	6.30	2.51	114	19	0.80	3.33	1971	1988	6.18	2.84	2.97	1.58	1.67	2.24	2.85	3.63	4.15	4.04	3.68	2.95
Petite Nation	Pq02Ld0001	Cond.	usie/c	1229	35	181	384	36	85	1971	1988	119	79	91	60	63	71	80	88	92	104	88	84
Petite Nation	Pq02Ld0001	Fe ex.	mg/l	2.59	1.61	50	9.40	0.10	0.88	1980	1983	0.41	0.78	0.28	2.40	0.20	0.63	1.90	0.26	1.02	0.48	0.52	0.11
Petite Nation	Pq02Ld0001	Fe tot.	mg/l	0.15	0.39	65	2.26	0.040	0.45	1976	1988	0.25	0.27	0.31	0.97	0.27	0.30	0.40	0.27	0.59	0.52	0.54	0.37
Petite Nation	Pq02Ld0001	HCO3 calc.	mg/l	497	22	16	117	23	33	1971	1987	58	28	29			23	27		26	30	31	27
Petite Nation	Pq02Ld0001	Hg ex.	ug/l	0.000	0.000	7	0.050	0.050	0.050	1976	1979		0.050		0.050					0.050	0.050	0.050	
Petite Nation	Pq02Ld0001	HN4 dis.	mg/l	0.000	0.017	71	0.090	0.010	0.032	1976	1983	0.033	0.046	0.047	0.042	0.036	0.032	0.022	0.029	0.027	0.023	0.028	0.030
Petite Nation	Pq02Ld0001	K dis.	mg/l	0.88	0.94	37	6.00	0.70	1.52	1971	1983	1.20	1.22	1.10	1.60	0.70	0.90	1.07	1.10	2.46	1.90	1.36	1.40
Petite Nation	Pq02Ld0001	Mg dis.	mg/l	0.080	0.28	2	2.00	1.60	1.80	1976	1979		1.60										
Petite Nation	Pq02Ld0001	Mg tot.	mg/l	0.44	0.66	68	5.80	0.70	1.89	1971	1983	1.35	1.63	1.67	1.63	1.57	1.60	2.64	1.93	2.21	2.36	1.93	1.60
Petite Nation	Pq02Ld0001	Mn ex.	mg/l	0.001	0.034	53	0.16	0.010	0.030	1980	1984	0.023	0.038	0.020	0.053	0.010	0.023	0.042	0.017	0.027	0.020	0.030	0.030
Petite Nation	Pq02Ld0001	Mn tot.	mg/l	0.000	0.010	65	0.060	0.010	0.019	1976	1988	0.017	0.014	0.020	0.032	0.012	0.016	0.022	0.018	0.024	0.018	0.017	0.017
Petite Nation	Pq02Ld0001	N dis.	mg/l	0.041	0.20	42	1.43	0.23	0.52	1985	1988	0.53	0.68	1.18	0.55	0.40	0.47	0.41	0.36	0.36	0.53	0.57	0.54
Petite Nation	Pq02Ld0001	N dis. kjeld.	mg/l	0.007	0.082	41	0.55	0.060	0.20	1976	1983	0.15	0.14	0.28	0.14	0.28	0.24	0.16	0.21	0.30	0.22	0.19	0.20
Petite Nation	Pq02Ld0001	N tot. kjeld.	mg/l	0.016	0.13	102	1.15	0.030	0.23	1979	1985	0.17	0.27	0.24	0.20	0.19	0.24	0.26	0.23	0.25	0.26	0.21	0.27
Petite Nation	Pq02Ld0001	Na dis.	mg/l	1.08	1.04	38	5.00	1.10	2.79	1971	1983	2.60	2.30	2.80	1.87	1.10	1.70	2.60	3.53	3.91	4.80	2.43	2.30
Petite Nation	Pq02Ld0001	NH4 tot.	mg/l	0.001	0.031	114	0.26	0.003	0.037	1979	1988	0.037	0.061	0.071	0.039	0.028	0.030	0.029	0.025	0.025	0.029	0.029	0.040
Petite Nation	Pq02Ld0001	NO3 + NO2	mg/l	0.10	0.32	192	2.70	0.090	0.29	1971	1988	0.41	0.51	0.40	0.25	0.18	0.18	0.20	0.16	0.21	0.24	0.30	0.55
Petite Nation	Pq02Ld0001	O2 dis.	mg/l	4.13	2.03	20	15	9.00	12	1971	1985		14		13	12			9.77	9.03	12	14	
Petite Nation	Pq02Ld0001	P dis. tot.	mg/l	0.000	0.009	105	0.060	0.006	0.014	1980	1985	0.014	0.013	0.015	0.017	0.016	0.009	0.015	0.011	0.019	0.012	0.012	0.009

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	SD	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Petite Nation	Pq02La0001	P susp.	ug/l	0.000	0.011	59	0.055	0.000	0.005	1984	1988	0.003	0.003	0.008	0.011	0.003	0.013	0.003	0.003	0.008	0.003	0.003	0.003
Petite Nation	Pq02La0001	P tot.	mg/l	0.001	0.022	11	0.085	0.014	0.029	1976	1987	0.085	0.018	0.014			0.054	0.038		0.017	0.016	0.022	
Petite Nation	Pq02La0001	pH	ph	0.16	0.40	124	8.00	4.50	7.32	1971	1988	7.50	7.29	7.38	7.03	7.23	7.40	7.39	7.45	7.42	7.53	7.22	7.20
Petite Nation	Pq02La0001	PO4 dis.	mg/l	0.000	0.010	42	0.060	0.010	0.013	1985	1988	0.010	0.010	0.010	0.012	0.012	0.026	0.021	0.010	0.010	0.011	0.010	0.010
Petite Nation	Pq02La0001	PO4 dis. ortho	mg/l			1	0.020	0.020	0.020	1976	1976											0.020	
Petite Nation	Pq02La0001	PO4 tot. inorg	mg/l	0.11	0.33	7	0.90	0.000	0.17	1971	1972	0.000	0.000					0.10		0.10		0.000	0.90
Petite Nation	Pq02La0001	Si react.	mg/l	1.65	1.29	53	6.70	0.60	4.35	1971	1985	4.96	5.43	4.77	4.35	3.65	3.63	4.22	3.80	3.93	5.03	4.35	3.47
Petite Nation	Pq02La0001	SO4 dis.	mg/l	27	5.17	116	45	1.50	11	1971	1988	17	11	13	7.79	9.54	8.64	8.72	9.43	9.89	13	12	10
Petite Nation	Pq02La0001	Sr tot.	mg/l	0.000	0.006	3	0.060	0.050	0.053	1982	1983		0.050						0.060				
Petite Nation	Pq02La0001	Temp.	deg c	67	8.17	221	25	0.000	9.90	1977	1988	0.69	0.53	1.19	5.40	11	18	22	21	17	9.22	3.07	1.00
Rideau	On02La0002	Al ex.	mg/l	0.001	0.036	3	0.070	0.000	0.040	1970	1970	0.070						0.050			0.000		
Rideau	On02La0002	Alk tot. CaCO3	mg/l	743	27	114	205	21	129	1970	1984	160	159	127	111	134	135	122	105	113	125	140	140
Rideau	On02La0002	BOD	mg/l	0.96	0.98	84	5.00	0.10	1.38	1970	1981	2.05	1.70	1.44	1.85	1.21	0.90	1.12	1.28	1.34	1.17	1.58	
Rideau	On02La0002	Ca tot.	mg/l	179	13	15	62	10	38	1970	1971	62	54	30	27	42	41	35	33	19	46		
Rideau	On02La0002	Cl dis.	mg/l	61	7.90	92	60	2.00	14	1970	1984	23	29	14	11	11	12	12	12	12	12	14	26
Rideau	On02La0002	Cond.	usie/c	4438	67	128	520	74	320	1970	1984	409	416	315	289	314	316	307	265	274	301	335	425
Rideau	On02La0002	daily av. disch.	m3/s	6105	78	71	467	3.99	49	1973	1981	34	29	188	101	40	14	10	9.73	35	32	46	49
Rideau	On02La0002	Fe ex.	mg/l	0.21	0.46	12	1.75	0.10	0.45	1970	1971	0.20	1.13	0.45	1.75	0.25	0.25	0.30	0.90		0.25	0.35	
Rideau	On02La0002	Fe tot.	mg/l	0.43	0.66	94	5.10	0.050	0.43	1972	1984	0.50	0.010	1.01	0.55	0.29	0.39	0.21	0.18	0.16	0.22	0.30	0.17
Rideau	On02La0002	Hg tot.	ug/l	0.000	0.008	15	0.030	0.010	0.017	1977	1984		0.010	0.010	0.030	0.010	0.010	0.010	0.030	0.015	0.020	0.020	0.020
Rideau	On02La0002	HN4 dis.	mg/l	0.005	0.068	103	0.37	0.002	0.062	1972	1984	0.072	0.16	0.11	0.054	0.036	0.036	0.070	0.042	0.048	0.039	0.021	0.054
Rideau	On02La0002	K dis.	mg/l	0.36	0.60	16	2.60	0.60	1.49	1970	1971	2.60	2.40	2.00	2.00	1.40	1.10	0.95	1.00	0.70	1.90		
Rideau	On02La0002	Mg dis.	mg/l	14	3.69	14	18	4.00	12	1970	1971	17	15	12	8.00	13	11	11	6.00	14	12	13	11
Rideau	On02La0002	Mg tot.	mg/l	28	5.30	59	45	2.00	13	1972	1984	17	15	12	9.04	12	18	12	10	11	11		
Rideau	On02La0002	Mn ex.	mg/l	0.000	0.019	5	0.10	0.050	0.072	1970	1971	0.060			0.080	0.050	0.070	0.10					
Rideau	On02La0002	Mn. tot.	mg/l	0.008	0.092	58	0.72	0.010	0.065	1972	1984	0.058	0.24	0.11	0.064	0.051	0.046	0.058	0.038	0.044	0.038	0.040	0.033
Rideau	On02La0002	N tot.	mg/l	0.66	0.81	72	7.40	0.56	1.00	1972	1984	2.24	1.18	1.15	0.91	0.71	0.81	1.00	0.85	0.80	0.83	0.81	1.08
Rideau	On02La0002	N tot. Kjeld.	mg/l	0.50	0.71	172	7.10	0.10	0.78	1970	1984	1.87	0.85	0.71	0.59	0.66	0.73	0.78	0.74	0.68	0.70	0.59	0.56
Rideau	On02La0002	Na dis.	mg/l	4.23	2.06	16	8.00	0.30	5.21	1970	1971	7.00	6.00	6.50	0.30	5.33	5.50	3.50	5.50	6.00	6.00		
Rideau	On02La0002	NH4 tot.	mg/l	0.010	0.10	18	0.33	0.010	0.12	1970	1971	0.33	0.32	0.19	0.12	0.030	0.070	0.12	0.18	0.040	0.040	0.050	
Rideau	On02La0002	NO3 + NO2	mg/l	0.022	0.15	17	0.66	0.010	0.15	1970	1971	0.22	0.19	0.20	0.12	0.060	0.060	0.37	0.065	0.090	0.16	0.11	
Rideau	On02La0002	NO3 dis.	mg/l	0.022	0.15	77	0.72	0.005	0.16	1972	1984	0.23	0.26	0.35	0.28	0.052	0.060	0.13	0.088	0.074	0.099	0.18	0.31
Rideau	On02La0002	NO3 dis.	mg/l	0.001	0.033	96	0.31	0.000	0.014	1970	1984	0.006	0.006	0.008	0.010	0.008	0.010	0.056	0.014	0.017	0.008	0.005	0.006
Rideau	On02La0002	O2 dis.	mg/l	6.75	2.60	125	18	5.50	10	1970	1984	12	13	13	13	9.16	8.89	7.91	7.71	8.44	9.98	12	12

Appendix C

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Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StdDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rideau	On02La0002	P tot.	mg/l	0.001	0.033	128	0.21	0.010	0.051	1970	1984	0.049	0.074	0.067	0.058	0.041	0.049	0.056	0.055	0.053	0.033	0.031	0.028
Rideau	On02La0002	pH		0.15	0.39	114	8.90	5.50	7.95	1970	1984	7.61	7.87	7.68	7.84	8.11	8.09	7.89	7.97	7.95	8.09	8.14	8.02
Rideau	On02La0002	PO4 dis	mg/l	0.000	0.017	70	0.092	0.002	0.019	1972	1980	0.013	0.014	0.029	0.010	0.011	0.019	0.036	0.027	0.030	0.008	0.005	0.004
Rideau	On02La0002	PO4 dis, ortho	mg/l	0.000	0.007	18	0.020	0.002	0.010	1970	1971	0.013	0.020	0.010	0.016	0.002	0.006	0.015	0.015	0.010	0.010	0.002	
Rideau	On02La0002	Si react.	mg/l	14	3.70	14	14	0.50	3.70	1970	1971	6.50	5.70	11	3.60	1.70	0.50	1.50	1.75	1.10	2.40		
Rideau	On02La0002	SO4 dis.	mg/l	12	3.51	16	26	13	17	1970	1971		18	20	14	17	15	13	18	14	21	18	
Rideau	On02La0002	Temp.	deg c	82	9.04	128	28	0.000	11	1970	1984	0.44	0.30	1.02	7.00	15	21	23	22	18	9.84	3.82	0.50
Rigaud	Pq02Lb0005	Alk tot. CaCO3	mg/l			1	205	205	205	1976	1976											205	
Rigaud	Pq02Lb0005	C tot.	mg/l			1	61	61	61	1976	1976											61	
Rigaud	Pq02Lb0005	C tot. inorg.	mg/l			1	46	46	46	1976	1976											46	
Rigaud	Pq02Lb0005	Ca dis.	mg/l			1	60	60	60	1976	1976											60	
Rigaud	Pq02Lb0005	Cl dis.	mg/l			1	14	14	14	1976	1976											14	
Rigaud	Pq02Lb0005	Cond.	usie/c			1	404	404	404	1976	1976											404	
Rigaud	Pq02Lb0005	Fe tot.	mg/l	7.80	2.79	3	5.70	0.50	2.51	1976	1978				1.33						5.70	0.50	
Rigaud	Pq02Lb0005	Hg ex.	ug/l	0.000	0.006	3	0.060	0.050	0.053	1976	1978				0.050					0.060	0.050	0.050	
Rigaud	Pq02Lb0005	HN4 dis.	mg/l			1	0.070	0.070	0.070	1976	1976											0.070	
Rigaud	Pq02Lb0005	K dis.	mg/l			1	3.00	3.00	3.00	1976	1976											3.00	
Rigaud	Pq02Lb0005	Mg dis.	mg/l			1	20	20	20	1976	1976											20	
Rigaud	Pq02Lb0005	Mn. tot.	mg/l	0.001	0.032	3	0.090	0.030	0.053	1976	1978				0.040					0.090	0.030	0.030	
Rigaud	Pq02Lb0005	N dis. kjeld.	mg/l			1	0.38	0.38	0.38	1976	1976											0.38	
Rigaud	Pq02Lb0005	Na dis.	mg/l			1	17	17	17	1976	1976											17	
Rigaud	Pq02Lb0005	NO3 + NO2	mg/l			1	1.30	1.30	1.30	1976	1976											1.30	
Rigaud	Pq02Lb0005	O2 dis.	mg/l			1	14	14	14	1976	1976											14	
Rigaud	Pq02Lb0005	P tot.	mg/l			1	0.23	0.23	0.23	1976	1976											0.23	
Rigaud	Pq02Lb0005	pH		0.030	0.17	3	8.20	7.90	8.00	1976	1978				8.20					7.90		7.90	
Rigaud	Pq02Lb0005	PO4 dis, ortho	mg/l			1	0.070	0.070	0.070	1976	1976											0.070	
Rigaud	Pq02Lb0005	Si react.	mg/l			1	5.00	5.00	5.00	1976	1976											5.00	
Rigaud	Pq02Lb0005	SO4 dis.	mg/l			1	38	38	38	1976	1976											38	
Rigaud	Pq02Lb0005	Temp.	deg c	27	5.20	3	10	0.000	5.83	1976	1978				10							0.000	
Rouge	Pq02Lc0013	Al ex.	mg/l	0.010	0.10	13	0.35	0.050	0.17	1982	1985		0.21		0.21	0.18			0.073			0.000	
Rouge	Pq02Lc0013	Alk tot. CaCO3	mg/l	24	4.94	114	40	4.20	12	1976	1987	11	15	13	6.73	7.24	11	15	13	13	9.89	10	16
Rouge	Pq02Lc0013	BOD	mg/l	0.49	0.70	6	3.00	1.10	1.73	1976	1978							1.93	1.53				
Rouge	Pq02Lc0013	C dis. inorg.	mg/l	0.50	0.71	71	4.00	1.00	2.42	1984	1987		3.35	3.04	1.67	1.64	2.33	2.28	2.80	2.83	2.56	2.43	2.33
Rouge	Pq02Lc0013	C dis. org.	mg/l	1.06	1.03	71	10	2.70	4.63	1984	1987		4.00	3.66	4.44	4.07	4.23	5.15	4.89	4.65	5.06	5.44	4.73

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StdDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rouge	Pq02Lc0013	C tot.	mg/l	24	4.89	179	44	3.00	12	1976	1983	22	12	11	9.92	9.85	12	9.97	12	13	12	11	17
Rouge	Pq02Lc0013	C tot. inorg.	mg/l	1.17	1.08	177	5.50	0.50	2.40	1976	1983	2.79	3.20	2.88	1.97	1.54	2.45	2.54	2.67	2.33	1.92	1.83	3.13
Rouge	Pq02Lc0013	Ca dis.	mg/l	0.96	0.98	15	6.50	3.10	4.89	1976	1979	5.60	5.40	6.50	3.10	3.90	5.25	5.00	3.80	5.10	4.00	5.10	4.80
Rouge	Pq02Lc0013	Ca tot.	mg/l	23	4.75	370	32	1.00	6.81	1971	1987	7.38	11	7.04	4.87	5.05	6.31	6.33	9.51	7.58	5.13	5.79	5.37
Rouge	Pq02Lc0013	Cl dis.	mg/l	9.93	3.15	382	23	0.20	3.75	1971	1987	5.36	7.49	4.57	2.16	2.32	4.06	3.30	4.03	3.80	2.24	2.78	2.78
Rouge	Pq02Lc0013	Cond.	usie/c	1447	38	496	228	18	66	1971	1987	83	96	85	53	47	64	58	84	70	51	55	55
Rouge	Pq02Lc0013	Fe ex.	mg/l	0.079	0.28	70	1.40	0.030	0.39	1978	1983	0.20	0.34	0.17	0.67	0.36	0.26	0.46	0.28	0.42	0.41	0.35	0.25
Rouge	Pq02Lc0013	Fe tot.	mg/l	0.055	0.23	101	1.49	0.050	0.38	1975	1987	0.16	0.41	0.25	0.60	0.26	0.32	0.51	0.35	0.39	0.44	0.30	0.27
Rouge	Pq02Lc0013	HCO3 calc.	mg/l	19	4.33	11	21	6.30	12	1986	1987			21	6.60	6.30	11	17	15	12	9.10	12	15
Rouge	Pq02Lc0013	Hg ex.	ug/l	0.000	0.021	29	0.14	0.050	0.057	1976	1979	0.050	0.050	0.050	0.050	0.080	0.080	0.050	0.053	0.050	0.070	0.050	0.050
Rouge	Pq02Lc0013	HN4 dis.	mg/l	0.000	0.019	100	0.090	0.010	0.029	1976	1983	0.037	0.048	0.054	0.043	0.025	0.019	0.017	0.023	0.018	0.022	0.019	0.037
Rouge	Pq02Lc0013	K dis.	mg/l	0.40	0.63	294	7.00	0.20	0.86	1971	1983	0.61	1.00	1.11	0.63	0.72	0.78	0.81	1.16	1.09	0.57	0.90	0.71
Rouge	Pq02Lc0013	Mg dis.	mg/l	0.13	0.36	15	1.70	0.50	1.17	1976	1979	1.00	1.30	1.40	0.80	0.50	1.45	1.70	0.60	1.40	1.10	1.10	1.40
Rouge	Pq02Lc0013	Mg tot.	mg/l	3.16	1.78	336	10	0.10	1.53	1971	1983	1.67	2.11	1.99	1.15	1.13	1.76	1.29	2.39	1.37	0.97	1.30	0.84
Rouge	Pq02Lc0013	Mn ex.	mg/l	0.000	0.018	75	0.11	0.010	0.025	1977	1984	0.017	0.023	0.013	0.039	0.023	0.010	0.028	0.014	0.027	0.024	0.029	0.022
Rouge	Pq02Lc0013	Mn tot.	mg/l	0.000	0.021	101	0.17	0.010	0.025	1975	1987	0.010	0.042	0.013	0.043	0.022	0.022	0.031	0.023	0.022	0.020	0.015	0.017
Rouge	Pq02Lc0013	N dis.	mg/l	0.011	0.10	43	0.63	0.17	0.35	1985	1987			0.41	0.54	0.35	0.27	0.31	0.27	0.26	0.35	0.32	0.46
Rouge	Pq02Lc0013	N dis. kjeld.	mg/l	0.006	0.077	66	0.50	0.10	0.20	1976	1983	0.19	0.15	0.20	0.21	0.20	0.23	0.18	0.20	0.23	0.20	0.15	0.23
Rouge	Pq02Lc0013	N tot. kjeld.	mg/l	0.20	0.45	147	3.20	0.080	0.32	1976	1985	1.09	0.26	0.18	0.21	0.19	0.16	0.26	0.41	0.25	0.21	0.16	0.77
Rouge	Pq02Lc0013	Na dis.	mg/l	6.60	2.57	295	17	0.20	3.29	1971	1983	3.63	5.79	3.78	2.13	2.57	3.92	2.43	3.48	3.38	1.87	2.92	2.23
Rouge	Pq02Lc0013	NH4 tot.	mg/l	0.025	0.16	154	0.83	0.001	0.077	1976	1987	0.38	0.14	0.039	0.033	0.034	0.024	0.043	0.067	0.038	0.025	0.028	0.24
Rouge	Pq02Lc0013	NO3 + NO2	mg/l	0.27	0.52	482	5.00	0.010	0.31	1971	1987	0.49	0.77	0.59	0.35	0.25	0.17	0.20	0.17	0.14	0.13	0.24	0.35
Rouge	Pq02Lc0013	O2 dis.	mg/l	8.72	2.95	48	15	1.00	11	1971	1985	15	14	14	12	11	7.80	7.85	9.57	9.54	12	14	5.20
Rouge	Pq02Lc0013	P dis. tot.	mg/l	0.004	0.063	118	0.69	0.006	0.018	1979	1985	0.15	0.014	0.013	0.013	0.010	0.016	0.020	0.014	0.012	0.010	0.008	0.011
Rouge	Pq02Lc0013	P susp.	ug/l	0.000	0.008	59	0.043	0.000	0.003	1984	1987		0.000	0.000	0.007	0.003	0.007	0.003	0.004	0.004	0.002	0.002	0.002
Rouge	Pq02Lc0013	P tot.	mg/l	0.001	0.038	47	0.14	0.006	0.035	1976	1987			0.014	0.095	0.029	0.067	0.021	0.026	0.013	0.013	0.014	0.081
Rouge	Pq02Lc0013	pH	ph	0.087	0.29	155	8.00	5.80	7.01	1976	1987	6.98	7.06	7.10	6.81	6.84	7.04	7.14	7.19	7.15	7.04	6.96	6.91
Rouge	Pq02Lc0013	PO4 dis.	mg/l	0.000	0.004	42	0.025	0.010	0.011	1985	1987		0.006	0.010	0.015	0.011	0.011	0.013	0.010	0.010	0.013	0.010	0.010
Rouge	Pq02Lc0013	PO4 dis. ortho	mg/l	0.000	0.004	9	0.020	0.006	0.008	1976	1977						0.007	0.007	0.007	0.007	0.007	0.013	0.007
Rouge	Pq02Lc0013	PO4 tot. inorg.	mg/l	0.012	0.11	63	0.83	0.000	0.054	1971	1976	0.023	0.16	0.11	0.13	0.017	0.037	0.020	0.038	0.024	0.047	0.072	0.022
Rouge	Pq02Lc0013	Si	mg/l	8.22	2.87	326	16	0.10	4.74	1971	1985	3.25	4.42	3.81	4.52	6.18	6.02	4.48	4.33	5.79	4.77	4.42	4.10
Rouge	Pq02Lc0013	SO4	mg/l	20	4.48	379	36	1.40	8.00	1971	1987	8.71	13	7.45	7.61	6.86	7.44	6.28	7.83	6.29	7.40	8.17	6.92
Rouge	Pq02Lc0013	Sr	mg/l	0.000	0.006	3	0.050	0.040	0.043	1982	1983		0.040		0.040				0.050				
Rouge	Pq02Lc0013	Temp	deg c	69	8.32	433	27	0.000	12	1976	1987	0.50	0.66	1.90	5.73	14	19	23	21	17	9.98	4.54	1.16

Appendix C

Table C2: Mean monthly chemistry of major tributaries in the Ottawa River basin, 1970-90 (calculated from Environment Canada, 1993a)

Tributary	Station no.	Variable	Unit	Var	StDev	Cnt	Max	Min	Avg	First	Last	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
South Nation	On02Lb0009	Al ex.	mg/l	0.011	0.10	3	0.28	0.090	0.16	1970	1970	0.28						0.090			0.11		
South Nation	On02Lb0009	Alk tot. CaCO3	mg/l	1921	44	105	242	14	146	1970	1984	161	147	125	126	155	137	163	144	113	161	176	173
South Nation	On02Lb0009	BOD	mg/l	1.37	1.17	81	6.00	0.40	2.04	1970	1981	2.33	3.18	3.22	2.28	1.32	1.60	1.95	2.80	1.71	1.77	1.82	0.90
South Nation	On02Lb0009	Ca tot.	mg/l	289	17	9	61	13	47	1970	1970	13			25	59	59	61	50	46	50	60	
South Nation	On02Lb0009	Cl dis.	mg/l	814	29	91	226	1.04	30	1970	1984	46	40	18	15	22	47	28	29	26	32	29	37
South Nation	On02Lb0009	Cond.	usiel/c	38432	196	120	2030	50	450	1970	1984	505	473	381	347	430	393	430	476	357	614	472	538
South Nation	On02Lb0009	daily av. disch.	m3/s	9568	98	84	677	0.43	45	1971	1981	12	21	287	70	41	34	39	6.18	11	26	40	45
South Nation	On02Lb0009	Fe ex.	mg/l	3.42	1.85	5	4.80	0.25	1.65	1970	1970	0.25			4.80	1.45	0.35				1.40		
South Nation	On02Lb0009	Fe tot.	mg/l	5.83	2.41	93	16	0.050	2.29	1971	1984	1.89	1.11	3.84	5.43	2.27	1.96	2.46	1.52	1.50	2.20	2.32	1.69
South Nation	On02Lb0009	Hg ex.	ug/l			1	0.050	0.050	0.050	1970	1970						0.050						
South Nation	On02Lb0009	Hg tot.	ug/l	0.000	0.005	13	0.030	0.010	0.021	1977	1984	0.020	0.020	0.030	0.030	0.020		0.020	0.020	0.015	0.020		0.020
South Nation	On02Lb0009	HNA dis.	mg/l	0.017	0.13	107	0.82	0.002	0.11	1971	1984	0.13	0.16	0.16	0.16	0.038	0.10	0.16	0.11	0.13	0.098	0.076	0.062
South Nation	On02Lb0009	K dis.	mg/l	1.32	1.15	9	5.10	1.30	3.34	1970	1970	1.30			3.00	3.20	2.80	3.40	3.00	3.30	5.10	5.00	
South Nation	On02Lb0009	Mg dis.	mg/l	19	4.30	9	15	4.00	11	1970	1970	4.00			4.00	11	14	13	13	14	14	15	16
South Nation	On02Lb0009	Mg tot.	mg/l	18	4.29	64	22	1.38	12	1971	1984	15	14	9.40	11	13	13	13	12	7.63	13	16	
South Nation	On02Lb0009	Mn ex.	mg/l	0.001	0.030	4	0.070	0.010	0.035	1970	1970	0.010			0.010			0.070			0.050		
South Nation	On02Lb0009	Mn. tot.	mg/l	0.003	0.058	58	0.35	0.014	0.078	1971	1984	0.067	0.062	0.17	0.17	0.069	0.061	0.055	0.046	0.068	0.078	0.050	0.050
South Nation	On02Lb0009	N tot.	mg/l	1.16	1.07	75	9.36	0.38	1.59	1971	1984	2.98	1.75	1.88	1.67	1.12	1.49	1.18	1.26	1.55	1.58	1.43	1.73
South Nation	On02Lb0009	N tot. kjeld.	mg/l	0.73	0.86	173	8.50	0.080	0.99	1970	1984	1.92	0.87	0.89	0.91	0.87	1.06	0.96	1.01	0.89	0.90	0.85	0.72
South Nation	On02Lb0009	Na dis.	mg/l	78	8.81	9	30	3.00	16	1970	1970	5.00			3.00	13	18	23	19	23	30	12	
South Nation	On02Lb0009	NH4 tot.	mg/l	0.005	0.074	10	0.28	0.050	0.13	1970	1970	0.12			0.12	0.14	0.24	0.10	0.050	0.080	0.10	0.070	
South Nation	On02Lb0009	NO3 + NO2	mg/l	0.14	0.38	8	1.22	0.020	0.32	1970	1970	0.15			0.33	0.19	0.20		0.020	0.29	0.12	1.22	
South Nation	On02Lb0009	NO3 dis.	mg/l	0.21	0.46	80	1.89	0.005	0.48	1971	1984	0.85	0.78	0.87	0.60	0.23	0.39	0.10	0.14	0.43	0.59	0.54	0.98
South Nation	On02Lb0009	NO3 dis.	mg/l	0.010	0.10	92	0.98	0.000	0.034	1970	1984	0.018	0.014	0.021	0.047	0.019	0.022	0.022	0.025	0.13	0.017	0.018	0.043
South Nation	On02Lb0009	O2 dis.	mg/l	6.14	2.48	114	16	0.10	9.79	1970	1984	9.64	11	9.90	10	9.87	9.20	9.43	8.32	9.49	9.00	11	12
South Nation	On02Lb0009	P tot.	mg/l	0.013	0.11	120	0.96	0.010	0.14	1970	1984	0.17	0.11	0.15	0.15	0.10	0.12	0.14	0.13	0.19	0.15	0.12	0.095
South Nation	On02Lb0009	pH	ph	0.15	0.39	112	9.20	6.80	7.88	1970	1984	7.77	7.59	7.51	7.66	7.97	8.09	8.11	8.08	7.82	7.84	8.15	7.78
South Nation	On02Lb0009	PO4 dis.	mg/l	0.002	0.045	72	0.23	0.010	0.074	1971	1981	0.11	0.069	0.099	0.088	0.045	0.049	0.071	0.073	0.066	0.085	0.075	0.041
South Nation	On02Lb0009	PO4 dis. ortho	mg/l	0.000	0.010	10	0.042	0.007	0.029	1970	1970	0.007			0.036	0.023	0.023	0.029	0.033	0.042	0.039	0.036	
South Nation	On02Lb0009	Si react.	mg/l	5.69	2.38	8	8.00	1.80	4.45	1970	1970	8.00			3.80		3.00	1.80	2.70	3.20	5.10	8.00	
South Nation	On02Lb0009	SO4 dis.	mg/l	195	14	9	55	14	30	1970	1970	14			18	46	22	27	23	24	41	55	
South Nation	On02Lb0009	Temp.	deg c	78	8.85	119	27	0.000	11	1970	1984	1.00	1.30	1.19	7.33	14	22	23	22	18	8.75	3.42	3.00