Canada Alberta Northwest Territories

Northern River Basins Study










NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 110

CONTRIBUTION OF INDUSTRIAL, MUNICIPAL, AGRICULTURAL AND GROUNDWATER SOURCES TO NUTRIENT EXPORT,

ATHABASCA, WAPITI AND SMOKY RIVERS, 1980 TO 1993






Prepared for the
Northern River Basins Study
under Project 2622-D1

by

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Published by the
Northern River Basins Study
Edmonton, Alberta
March, 1997

CANADIAN CATALOGUING IN PUBLICATION DATA

Chambers, Patricia A.

Contribution of industrial, municipal, agricultural
and groundwater sources to nutrient export, Athabasca,
Wapiti and Smoky Rivers, 1980 to 1993

(Northern River Basins Study project report,
ISSN 1192-3571 ; no. 110)
Includes bibliographical references.
ISBN 0-662-24636-5
Cat. no. R71-49/3-110E

1. Water quality -- Alberta -- Athabasca River.
2. Water quality -- Alberta --Wapiti River.
3. Water quality -- Alberta --Smoky River.
4. Groundwater -- Alberta -- Athabasca River.
5. Groundwater -- Alberta --Wapiti River.
6. Groundwater -- Alberta --Smoky River.
I. Dale, Alec R.
II. Northern River Basins Study (Canada)
III. Title.
IV. Series.

TD387.C42 1997 363.73'94'097123 C96-980213-7

PREFACE:

The Northern River Basins Study was initiated through the "Canada-Alberta-Northwest Territories Agreement Respecting the Peace-Athabasca-Slave River Basin Study, Phase II - Technical Studies" which was signed September 27, 1991. The purpose of the Study is to understand and characterize the cumulative effects of development on the water and aquatic environment of the Study Area by coordinating with existing programs and undertaking appropriate new technical studies.

This publication reports the method and findings of particular work conducted as part of the Northern River Basins Study. As such, the work was governed by a specific terms of reference and is expected to contribute information about the Study Area within the context of the overall study as described by the Study Final Report. This report has been reviewed by the Study Science Advisory Committee in regards to scientific content and has been approved by the Study Board of Directors for public release.

It is explicit in the objectives of the Study to report the results of technical work regularly to the public. This objective is served by distributing project reports to an extensive network of libraries, agencies, organizations and interested individuals and by granting universal permission to reproduce the material.

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NORTHERN RIVER BASINS STUDY
PROJECT REPORT RELEASE FORM

This publication may be cited as:

Chambers, P. A. and Dale, A. R. 1997. ***Northern River Basins Study Project Report No. 110, Contribution of Industrial, Municipal, Agricultural and Groundwater Sources to Nutrient Export, Athabasca, Wapiti and Smoky Rivers, 1980 to 1993.*** **Northern River Basins Study, Edmonton, Alberta.**

Whereas the above publication is the result of a project conducted under the Northern River Basins Study and the terms of reference for that project are deemed to be fulfilled,
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this publication be subjected to proper and responsible review and be considered for release to the public.

F. J. Wrona
(Dr. Fred J. Wrona, Science Director)

14 May 96
(Date)

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(Dr. P. A. Larkin, Ph.D., Chair)

24 May /96
(Date)

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Lucille Partington
(Lucille Partington, Co-chair)

May 29/96
(Date)

Robert McLeod.
(Robert McLeod, Co-chair)

May 21/96
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CONTRIBUTION OF INDUSTRIAL, MUNICIPAL, AGRICULTURAL AND GROUNDWATER SOURCES TO NUTRIENT EXPORT, ATHABASCA, WAPITI AND SMOKY RIVERS, 1980 TO 1993

STUDY PERSPECTIVE

Nutrients (nitrogen and phosphorus) have an important role in regulating the productivity of aquatic environments and the Northern River Basins Study (NRBS) Board was interested in how these would influence water quality and peoples use of the rivers. Research was undertaken by NRBS to determine the sources of nutrient inputs and their relative contribution of nutrients to the river. Some sources are very evident (point sources) while others are not (non-point). There is considerable difficulty in distinguishing the contribution of non-point sources because of the difficulty in measuring their inputs. GROUNDWATER sources fell into this latter category.

As part of a major initiative to better understand the contribution and role of nutrients in the aquatic environments of the Peace, Athabasca and Slave rivers, a project was undertaken to analyse existing sources of nutrient data in an attempt to better understand the relative contributions of point and non-point sources. This report describes the results of the data analysis done with information existing in the regulatory and industrial sectors.

Results from this project indicate that while municipal and industrial (pulp mill) sources account for a small percentage of the total annual nutrient budget of these rivers, they are seasonally significant during periods of low flow. Municipal and pulp mill sources are also the most significant contributor of nutrients that are readily bioavailable (easily converted into biological forms). Increased plant growth is evident in the rivers below Jasper, Hinton, Whitecourt, Athabasca, Fort McMurray and Grande Prairie. This increased plant growth has also been transferred to the higher trophic levels as noted in the increased densities of invertebrates.

Related Study Questions

2) What is the current state of water quality in the Peace, Athabasca and Slave river basins, including the Peace-Athabasca Delta?

5) Are the substances added to the rivers by natural and man made discharge likely to cause deterioration of the water quality?

7) What concentrations of dissolved oxygen are required to seasonally to protect the various life stages of fish, and what factors control dissolved oxygen in the rivers?

13a) What predictive tools are required to determine the cumulative effects of man-made discharges on the water and aquatic environment?

13b) What are the cumulative effects of man-made discharges on the water and aquatic environment?

14) What long term monitoring programs and predictive models are required to provide an ongoing assessment of the state of the aquatic ecosystem? These programs must ensure that all stakeholders have the opportunity for input.

Examination of chemical ions in river water suggests that GROUNDWATER is not a significant nutrient input during the winter.

Examination of the existing monitoring programs and data revealed the almost entire absence of data on the possible contributions of non-point sources to nutrient loads in the northern rivers. Researchers generally believe the large changes in land use patterns now taking place in the boreal forest may have substantial impacts on nutrient loading, particularly in the smaller tributaries where the use of bioavailable nutrients may be more readily possible.

REPORT SUMMARY

The aim of this report was to assess the sources of nitrogen and phosphorus to the Athabasca and Wapiti-Smoky rivers and evaluate the need to consider groundwater contributions when undertaking simulation modelling of chemical parameters of the Athabasca River during winter. To address the first objective, longitudinal trends in nitrogen (N) and phosphorus (P) were examined for each river system in relation to point-source inputs and the contributions of anthropogenic point sources and agricultural activity to the rivers' nutrient loads were quantified. The importance of groundwater during winter was assessed by examining hydrologic mass balances and changes in dominant ion proportions.

Analysis of long-term (1980 or 1989 to 1993) median values of total phosphorus (TP) and total nitrogen (TN) from 10 sites showed that nutrient concentrations varied along the length of the Athabasca River and were lowest upstream of Jasper Townsite, and increased between Jasper and Hinton and again downstream of Hinton. Thereafter, TN concentrations increased steadily along the river to Fort McMurray. In contrast, TP concentrations returned to background by 170 km downstream of Hinton, increased downstream of Whitecourt, and then remained relatively constant along the remainder of the river. Of the 721 TP measurements from the Athabasca River between 1980-93, 146 measurements or 20% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP of 0.05 mg/L P. Most of these exceedances occurred during summer and were likely due to high particulate P concentrations. The *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by only 2% of the samples. TP and TN export in the Athabasca River increased from 80 and 298 tonnes/y, respectively, near the headwaters (Athabasca River below Snaring River) to 2311 and 13670 tonnes/y, respectively at Old Fort, with 94% of the TP and 87% of the TN export occurring during the high flow season. On an annual basis, continuously-discharging industrial and municipal sources contributed 6 to 16% of the TP and 4 to 10% of the TN load. With the exception of Jasper, < 2% of the annual TP and TN load was attributable to municipal sources. However, during low flows, point sources contributed 37% of the TP load (27% from pulp mills and 10 % from municipalities) and 13% of the TN load (7% from pulp mill and 5% from municipalities) at Old Fort. Most of the non-point source TP and TN load was derived from run-off from forested land. TP losses from fertilized cropland were estimated to be less than 10% of the load from forested land.

For the Wapiti-Smoky rivers, only three sites have long-term (1980 or 1991 to 1993) year-round chemistry data. Analysis of these data showed that on an annual basis, TP and TN concentrations increased along the Wapiti River from upstream of Grande Prairie to the river mouth; concentrations were lower in the Smoky River at Watino than at the mouth of the Wapiti River. Of the 27 TP measurements at the mouth of the Wapiti River, 20 measurements or 74% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP of 0.05 mg/L P. The fact that the percent of exceedances increased from 12 to 74% from upstream of Grande Prairie to the mouth of the Wapiti River suggests that P from the City of Grande Prairie and Weyerhaeuser Canada Ltd. contributed to non-compliance with the TP guideline. The *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by 19% (*n*=26) of the samples from the Wapiti River near the mouth compared to no TN exceedances (*n*=21) for samples from upstream of

Grande Prairie, again suggesting that exceedances are related to nutrient loading from the Grande Prairie sewage treatment plant and mill. TP and TN export in the Wapiti River increased from 125 and 1018 tonnes/y, respectively, near the headwaters (Wapiti River at highway 40) to 2442 and 6421 tonnes/y, respectively at Watino, with 88% of the TP and 82% of the TN export occurring during the high flow season. In the Wapiti River, Grande Prairie sewage and the Weyerhaeuser pulp mill contributed 10 and 13%, respectively, of the annual TP load and 7 and 13%, respectively, of the annual TN load. However, during low flows, point sources contributed 41% of the TP load (24% from the pulp mill and 18% from Grande Prairie) and 34% of the TN load (22% from the pulp mill and 12% from Grande Prairie) in the Wapiti River. TP losses from cropland (79 tonne/y) were similar to losses from forested land (109 tonne/y) in the Wapiti River basin.

Examination of flow budgets and ionic composition of the mainstem surface waters of the Athabasca River for the 1989 to 1993 winters indicated that, for most winters, it is unlikely that there are large localized inputs of groundwater during winter. Comparison of the sum of headwater and tributary flows with the measured flow at Fort McMurray showed that the percentage of downstream discharge accounted for by known sources was, on average, 86% (66 to 106% range). While this unaccounted discharge may be due to groundwater inputs, some of this discrepancy is undoubtedly due to difficulties in measuring discharge under-ice cover. With respect to ionic composition, increases in the proportion of Na+K were observed downstream of Hinton, Whitecourt and Fort McMurray and related to inputs from the Hinton mill and sewage, Millar Western Pulp Ltd. and Whitecourt sewage effluents, and the Clearwater River. There were no changes in ionic proportions that could not be attributed to effluent or tributary inputs, again indicating that large localized inputs of groundwater during winter were unlikely.

While pulp mills contribute 4% of the annual TP load in the Athabasca River at Old Fort and 1% of the annual TP load in the Smoky River near Watino, their nutrient loading still produces ecological consequences. Increased periphyton growth has been observed during autumn downstream of Jasper, Hinton, Whitecourt, Athabasca, Fort McMurray and Grande Prairie. The effect of enhanced periphyton production due to effluent loading has been transferred to higher trophic levels in the food web with benthic invertebrate communities downstream of all pulp mill discharges showing increased densities. These nutrient impacts on riverine biota are due to the substantial contribution of nutrients from pulp mills and certain sewage discharges (e.g., Grande Prairie) during low flows. In addition, the bioavailable forms of N and P (which are responsible for increased aquatic plant growth) are proportionately more abundant in pulp mill and municipal effluents than in natural waters. This means that our calculations based on total N and P loading would underestimate the contribution of pulp mills and municipalities to the rivers' bioavailable nutrient loads. Our analysis of N and P contributions also highlighted the fact that data are almost entirely lacking on the contribution of non-point sources to nutrient loads in the Northern Rivers. While contributions can be estimated from the limited data for Alberta and from data for other parts of the world, the large changes in landuse patterns that have taken place and continue to occur in the boreal forest (e.g., agricultural land clearing, timber harvesting, oil and gas activities) may have substantial impacts on nutrient loading particularly to tributaries of the Peace and Athabasca Rivers.

ACKNOWLEDGEMENTS

We thank Colleen Pollock for her review of nutrient export coefficients and their relationship to drainage area, and Alberta Environmental Protection and Environment Canada, Atmospheric Environment Branch for nutrient and discharge data for the Athabasca, Wapiti and Slave rivers. This study was funded by the Northern River Basins Study.

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1.0 INTRODUCTION

The critical role of nutrients (nitrogen and phosphorus) in regulating the productivity and trophic status of aquatic systems is well known and has been widely studied (Schindler *et al.* 1971, Dillon and Rigler 1974). In the case of streams and rivers, nutrient addition as a result of sewage, industrial or agricultural inputs has been shown to increase periphyton standing crop as well as benthic invertebrate and fish growth rates (Cole 1973, Peterson *et al.* 1985, Perrin *et al.* 1987, Johnston *et al.* 1990). Fish standing crop for rivers in North America has also been found to be correlated with total phosphorus concentrations (Hoyer and Canfield 1991). However, while moderate nutrient additions to unproductive rivers can enhance productivity, nutrient additions to productive systems can cause environmental degradation. For example, nutrient enrichment by bleached kraft pulp mill and sewage treatment plant (STP) effluents to the Thompson River, British Columbia, at Kamloops resulted in a massive increase in algal biomass 20-40 km downstream of Kamloops Lake (Bothwell 1992). Similarly, Marcus (1980) found that nitrogen loading from a reservoir discharge increased the biomass and changed the species composition of periphyton communities in Hyalite Creek, Montana. Nutrient loading to the Rhine River, Europe, has resulted in such excessive biotic production that the lower Rhine is a net producer of carbon dioxide (formed by the oxidation of decomposing organisms) (Buhl *et al.* 1991). Nitrification can also affect the dissolved oxygen regime of enriched rivers such that the nitrification of ammonium to nitrite and nitrate has been found to depress dissolved oxygen concentrations in the Willamette River, Oregon (Dunnette and Avedovech 1983) and the Passaic River, New Jersey (Cirello *et al.* 1979).

The aim of this report was to: (1) assess nitrogen (N) and phosphorus (P) loading to the Athabasca and Wapiti-Smoky rivers, and (2) evaluate the need to consider groundwater contributions when undertaking simulation modelling of chemical parameters in the Athabasca River during winter. This work forms part of the Northern River Basins Study (NRBS), a joint study between the governments of Canada, Alberta and the Northwest Territories. The aim of the NRBS is to gather comprehensive information on water quality, fish and fish habitat, riparian vegetation and wildlife, hydrology and use of aquatic resources for the Peace, Athabasca and Slave River basins. This information is then used to predict and assess the cumulative effects of development on the aquatic environment of these basins within Alberta and the Northwest Territories.

To assess N and P contributions to the Northern Rivers, we examined: (1) longitudinal trends in nutrient chemistry in relation to point-source inputs, (2) the contribution of anthropogenic point sources to the rivers' nutrient loads, and (3) the potential contribution of land-use practices to nutrient loading. Nutrient loads from nine municipalities and five pulp mills in the Athabasca river drainage basin and three municipalities and one pulp mill on the Wapiti-Smoky River were evaluated in relation to in-stream nutrient concentrations (Chapter 2). Point-source contributions were then related to total phosphorus (TP) and nitrogen (TN) export at five sites along the Athabasca River and at three sites on the Wapiti-Smoky river system (Chapter 3). Exports were calculated from measurements of discharge and TP and TN concentrations. To assess anthropogenic nutrient loading from non-point sources, Geographical Information Systems (GIS) software was used to determine land-use characteristics of the Athabasca and Wapiti-Smoky drainage basins. Nitrogen and phosphorus export coefficients from the literature were then applied to each land-use type (Chapter 4). Previous work showed that TP loading to the

Athabasca River totalled 2 million kg/y with non-point sources contributing 95% of the load (Sentar Consultants Ltd. 1994). Previous calculations of TP load to the Athabasca River were re-assessed (Chapter 4) in response to concerns raised regarding the need to scale export coefficients as a function of drainage basin area and consider nutrient retention in large lakes, and since accurate data on landuse in the Athabasca basin are now available through geographic information systems. Using the validated approach, loadings were then calculated for TP, soluble reactive phosphorus (SRP) and TN for the Athabasca and Wapiti-Smoky rivers (Chapter 4). Estimates of potential loads of N and P from fertilizer application to croplands in the Athabasca and Wapiti rivers were also calculated and compared to estimates derived from loading coefficients. Finally, we evaluated the need to consider groundwater contributions when undertaking simulation modelling of the Athabasca River during winter by examining hydrologic mass balances and changes in dominant ion proportions (Chapter 5).

2.0 SITE DESCRIPTION

2.1 THE ATHABASCA RIVER

The Athabasca River originates in the Rocky Mountains of west-central Alberta in Jasper National Park. It then flows northeast across the boreal foothills and boreal mixed-wood ecoregions of Alberta to Lake Athabasca where it joins with the Peace River to form the Slave River (Figure 2.1). The latter flows into Great Slave Lake which drains via the Mackenzie River to the Beaufort Sea. The Athabasca River is not regulated. Mean daily flows at the Town of Athabasca average 407 m^3/s (1980-1993) with peak flows occurring in June after mountain snow-pack melt (1016 m^3/s June monthly mean, 1980-1993) and lowest flows in February (62 m^3/s February monthly mean, 1980-1993) (Environment Canada 1994).

Concern about water quality in the Athabasca River dates from the 1950's when the first pulp mill became operational. Currently, nine municipalities discharge continuously to the Athabasca River or its tributaries (Table 2.1) as well as the Town of Hinton which discharges with the Weldwood of Canada Ltd. effluent. In addition, 40 municipalities and two oil sands extraction plants discharge sewage lagoons once or twice per year (fall and sometimes spring) to rivers, creeks and lakes in the Athabasca drainage basin. One community (Lac la Biche) has continuous discharge of primary-treated effluent to a small lake (Field Lake) in the watershed.

In 1957, Northwest Pulp and Power Ltd. (now operated by Weldwood of Canada Ltd.) commenced operations in Hinton (Table 2.2). The mill is a bleached kraft plant and up to 1966, discharged minimally-treated effluent (i.e., from a facultative settling pond). Changes in operating licenses and mill technology have reduced effluent loading from the mill. In 1967, a primary clarifier (for removing solids) and aerated lagoons (five-day retention time) were installed to provide secondary treatment, with the latter expanded in 1975. The largest change occurred in 1990 when oxygen delignification and chlorine dioxide substitution were introduced and the effluent clarifier and aerated lagoons upgraded; 100% chlorine dioxide substitution was achieved in June 1993. Between August 1988 and late 1990, three chemi-thermomechanical mills started operations in the basin (Table 2.2); another kraft mill (Alberta-Pacific Forest Industries Inc., AlPac) became operational in September 1993. TP and TN loads to the river from all mills totalled 331 and 1033 kg/d (Table 2.2). There are also two oil sands projects in the basin but only one (Suncor Inc. Oil Sands Group) with continuous discharge of utility wastewater (from settling and retention basins plus an American Petroleum Institute (API) separation for oily wastewater) (Table 2.3). Other activities in the basin include four active coal mines, 67 gas plants, another oil sands project and 12 gravel-washing enterprises; however, all have little or no discharge (Alberta Environmental Protection 1995b).

2.2 WAPITI-SMOKY RIVERS

The Wapiti River arises in the Rocky Mountains of east-central British Columbia, south of Dawson Creek (Figure 2.1). It then flows east across the boreal uplands, boreal foothills and boreal mixed-wood

Figure 2.1 The Athabasca and Wapiti-Smoky river systems showing locations of continuous municipal, pulp mill and industrial discharges.

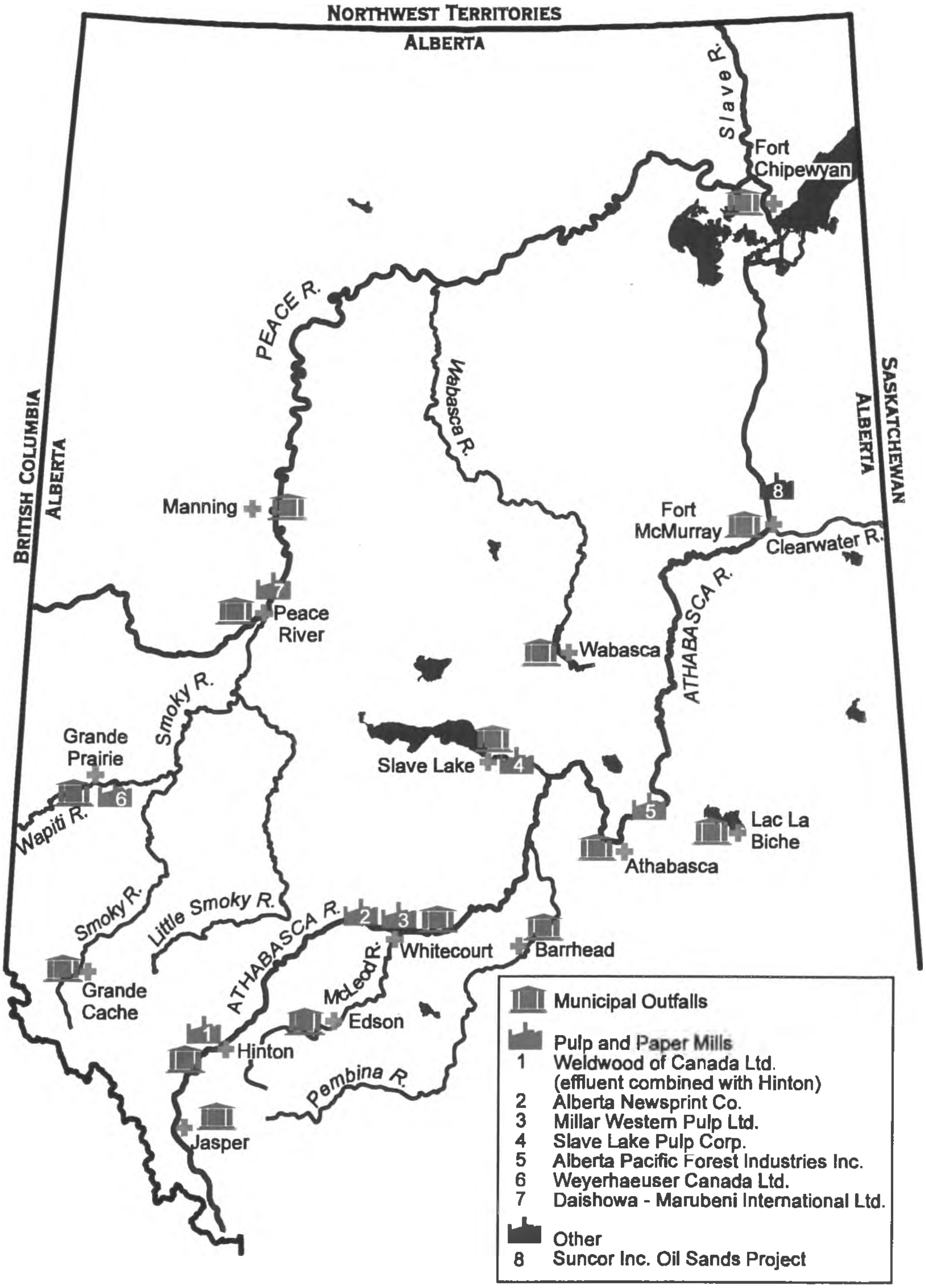

Table 2.1 **Effluent discharge and loads of total phosphorus (TP) and total nitrogen (TN) for municipalities with continuous discharge in the Athabasca and Wapiti-Smoky river basins. Discharge data from the NRBS *Municipal and Non-Pulp Mill Industrial Effluents Database* (Sentar Consultants Ltd. 1995). Nutrient concentrations from Alberta Environmental Protection winter water quality surveys (1989-1993) and database of D. Prince and S. Stanley (University of Alberta, Department of Civil Engineering). Nutrient concentrations were multiplied by mean discharge to give loads. (Data are given in detail in Appendix B). Note: Hinton municipal effluent is discharged with Weldwood of Canada Ltd. effluent; N/A is not available. Population data from Statistics Canada (1992).**

Source	Population (in 1991)	Effluent Treatment	Receiving Water	TP (kg/d)	TN (kg/d)	Discharge (m^3/d)
Athabasca River						
Jasper	3619	aerated stabilization basin	Athabasca River	16.8	78.6	3948
Edson	7323	aerated stabilization basin	McLeod River	16.2	60.6	3954
Whitecourt	6938	extended aeration activated sludge	Athabasca River	12.4	60.7	3417
Barrhead[1]	4160	aerated stabilization basin	Paddle River	N/A	N/A	N/A
Slave Lake	5607	aerated stabilization basin	Lesser Slave River	9.4	62.1	2730
Athabasca	1965	aerated stabilization basin	Athabasca River	4.6	24.7	952
Lac La Biche	2549	aerated stabilization basin	Field Lake	5.9	32.6	1425
Fort McMurray	34706	aerated stabilization basin	Athabasca River	26.6	344.2	14000
Fort Chipewyan	537	facultative lagoons	Riviere des Rochers	N/A	N/A	N/A
Wapiti-Smoky River						
Grande Cache	3842	extended aeration activated sludge	Smoky River	8.1	32.3	2032
Grande Prairie[2]	28271	rotating biological contactor	Wapiti River	53.3	249	10728

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[1] Barrhead sewage is discharged for five months over summer and is heldback for the remaining seven months of each year.

[2] Grande Prairie alternates two weeks of discharge and two weeks of holdback.

Table 2.2 **Total phosphorus (TP) and total nitrogen (TN) loads from pulp mills in the Athabasca and Wapiti-Smoky drainage basins. TP and TN loads were obtained for 1990-1993 from the Northern River Basins Study database *Northdat* (McCubbin and AGRA Earth and Environmental 1995) with the exception of TP and TN loads for Alberta Pacific Forest Industries Inc. which were obtained directly from the mill. (Results presented as mean±standard error with number of samples in brackets). (Data are given in detail in Appendix B).**

Pulp Mill	Location	Type	Start Up	Effluent Treatment	TP (kg/d)	TN (kg/d)
Weldwood of Canada Ltd.	Hinton	Kraft Pulp	1957 Expansion in 1990	ASB[1]	79±3(203)[2]	535±15(138)
Alberta Newsprint Company (1994 data)	Whitecourt	CTMP[3] and paper	Aug. 1990	Extended aeration AST[4]	92±5(176)	94±14(56)
Millar Western Pulp Ltd.	Whitecourt	CTMP	Aug. 1988	Extended aeration AST	34±2(213)	124±9(126)
Slave Lake Pulp Corp.	Slave Lake	CTMP	late 1990	AST	54±5(207)	103±8 (40)
Alberta Pacific Forest Industries Inc.	Athabasca	Kraft Pulp	Sept. 1993	AST	72±4(53)	177±20 (52)
Weyerhaeuser Canada Ltd.	Grande Prairie	Kraft Pulp	1973	ASB	72±3(214)	469±26(50)

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[1] Aerated Stabilization Basins

[2] Hinton municipal sewage is combined and discharged with Weldwood effluent

[3] Chemi-thermomechanical pulp

[4] Activated Sludge Treatment

Table 2.3 **Effluent discharge and loads of total phosphorus (TP) and total nitrogen (TN) for non-pulp mill industries with continuous discharge in the Athabasca and Wapiti-Smoky river basins.**

Source	Start Up	Effluent Treatment	Receiving Water	TP (kg/d)	TN (kg/d)	Discharge (m^3/d)	Reference
Athabasca River Suncor Inc. Oil Sands Group	1967	retention basin + American Petroleum Institute (API) separation system for oily wastewater	Athabasca River	6.86	42.4	38863	Discharge from NRBS *Municipal and Non-Pulpmill Effluent Database* (Sentar Consultants Ltd. 1995) and TP, TDP, and TN concentrations from Alberta Environment winter water quality surveys (1988-1994)
Alberta Power Ltd. H.R. Milner station	N/A	process wastewater	Smoky River	0.18	1.04 (TKN)	1469	Discharge from Shaw *et al.* (1990) after Nagendran *et al.* (1989) and TP and TKN concentrations from Sentar Consultants Ltd. (1994).

ecoregions of Alberta and converges with the Smoky River 42 km downstream of Grande Prairie. The Wapiti River is not regulated. Mean daily flows at Grande Prairie average 88 m^3/s (1980-1993) with peak flows occurring in June after mountain snow-pack melt (297 m^3/s June monthly mean, 1980-1993) and lowest flows in February (12 m^3/s February monthly mean, 1980-1993) (Environment Canada 1994).

The Smoky River originates in the Rocky Mountains of west-central Alberta, northwest of the Town of Jasper (Figure 2.1). It then flows northeast across the boreal uplands, boreal foothills and boreal mixed-wood ecoregions of Alberta and is joined by the Wapiti River. The Smoky River continues north and drains into the Peace River near the Town of Peace River. The Smoky River is not regulated. Mean daily flows near Watino average 315 m^3/s (1980-1993) with peak flows occurring in June after mountain snow-pack melt (921 m^3/s June monthly mean, 1980-1993) and lowest flows in February (43 m^3/s February monthly mean, 1980-1993) (Environment Canada 1994).

The only source of continuous-discharge industrial effluent on the Wapiti-Smoky rivers is the Weyerhaeuser Canada Ltd. (formerly Procter and Gamble Cellulose Ltd.) bleached kraft pulp mill at Grande Prairie (Table 2.2). The mill began operations in 1973 and discharged effluent treated in a primary clarifier and aerated lagoons. Upgrades to the mill included a switch from 25 to 70% chlorine dioxide substitution in fall 1990 and then to 100% substitution in July 1992. In addition to the pulp mill, there are two municipalities with continuous discharge to the basin: Grande Prairie to the Wapiti River (the town discharges for a two-week period followed by a two week hold-back) and Grande Cache to the Smoky River (Table 2.1). There are also 28 other communities in the Wapiti-Smoky drainage basin which discharge sewage lagoons once or twice yearly to the rivers and their tributaries. The Alberta Power Ltd. H.R. Milner thermal electric power station near Grande Cache discharges process wastewater to the Smoky River (Table 2.3). There are also 20 natural gas processing plants in the Wapiti-Smoky drainage (Alberta Environmental Protection 1995b).

3.0 LONGITUDINAL PATTERNS IN NITROGEN AND PHOSPHORUS IN THE ATHABASCA AND WAPITI-SMOKY RIVERS

3.1 INTRODUCTION

Longitudinal changes in N and P concentrations in the Athabasca and Wapiti-Smoky rivers have been examined by Clayton (1972) for the Athabasca River from 1966-1971, Hamilton *et al.* (1985) for the Athabasca River from 1970-1985, Noton and others (Noton and Shaw 1989, Noton 1992, Noton and Saffran 1995) for the Athabasca and Wapiti-Smoky rivers during winter low-flow periods, Noton *et al.* (1989) for the Wapiti-Smoky River during spring and fall 1983, and Sentar Consultants Inc. (1994) who summarized data up to 1993 on longitudinal changes, temporal patterns and point sources of nutrient loading. Their results showed that during winter low flows, elevated N and P concentrations occurred downstream of most of the major industrial and municipal effluent outfalls. Little attention has been directed at examining changes in nutrient concentrations for other seasons and assessing the relative contribution of point-source anthropogenic inputs to N and P loads in the rivers, although the recent *Alberta's State of the Environment Comprehensive Report* (Alberta Environmental Protection 1995a) notes that during winter, pulp mills contribute 36 and 11% of the TP in the Athabasca and Wapiti-Smoky rivers, respectively, while municipalities are a major source of ammonia (34 and 15%, respectively).

In this chapter, we examine changes in TP and TN concentrations in the Athabasca and Wapiti-Smoky rivers annually and during periods of low (December-April) and high (May-November) flow. The relative contribution of anthropogenic point sources to the nutrient load in the rivers was then determined for several locations along each river.

3.2 METHODS

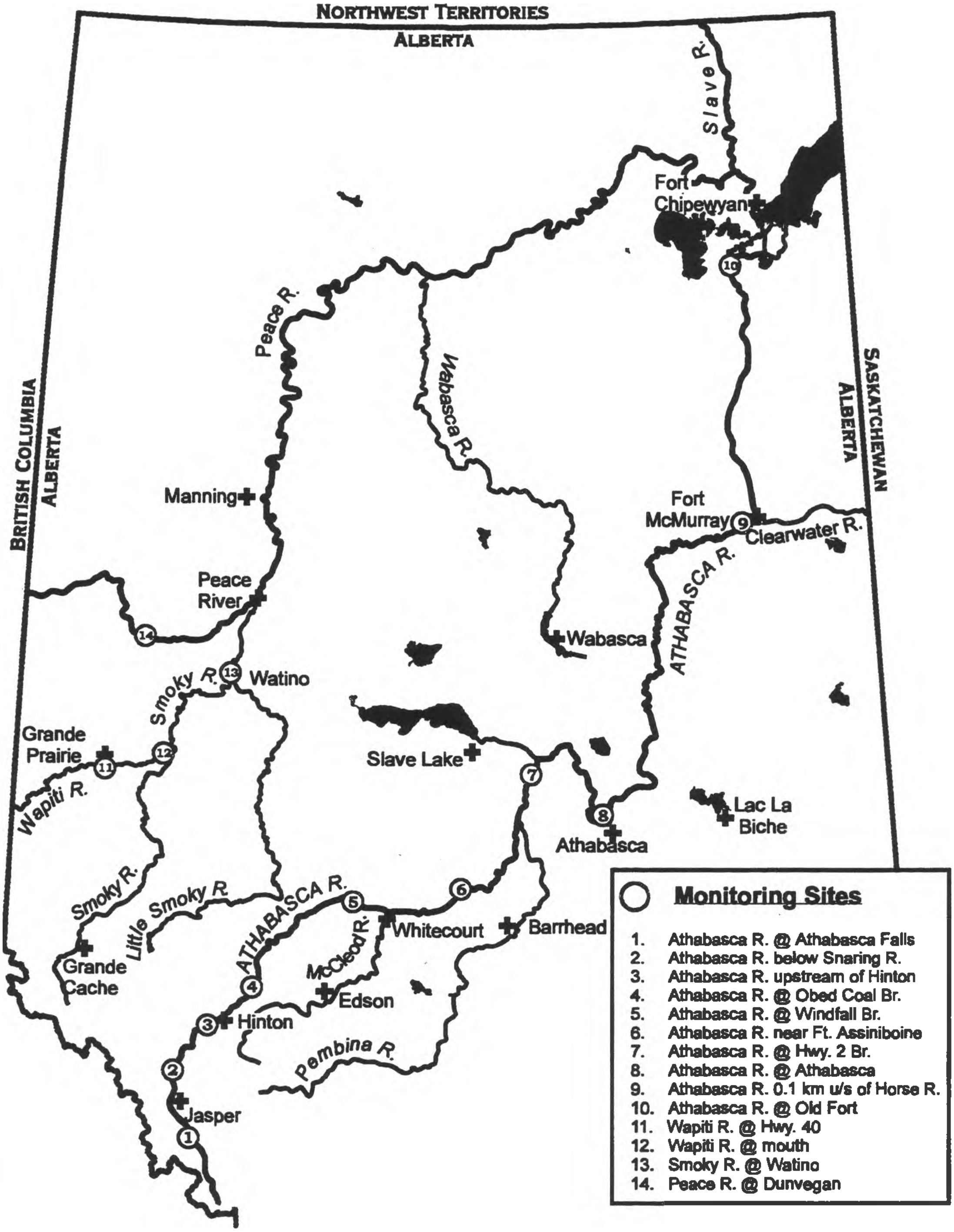
3.2.1 Instream Nutrient Concentrations and Loads

Data on TP and TN concentrations were obtained from Alberta Environmental Protection and Environment Canada for ten stations on the Athabasca River, two stations on the Wapiti River and one station on the Smoky River (Table 3.1) (Figure 3.1). To assess longitudinal changes in nutrient concentrations, TP and TN values for the Athabasca River are presented as 50th (median), 25th and 75th percentiles. Quartiles were used to assess changes in nutrient concentrations because, unlike mean values, quartiles are not strongly affected by high or low values and they permit the use of values below analytical detection limits (Helsel 1990). Seasonal variation in nutrient concentrations was evaluated by partitioning the data into high (May-November) and low (December-April) flow seasons. (There were insufficient data to assess nutrient concentrations during fall (September-October) when primary productivity in these systems is greatest.)

Table 3.1 **Sites on the Athabasca, Wapiti and Smoky rivers for which nitrogen and phosphorus data are available and the associated sites with discharge data. Data from these sites were used in calculating nutrient loads. (n/a indicates data not available.)**

Sites with nitrogen and phosphorus data	Associated sites with discharge data	Years of available data (number of dates with nutrient data)
Athabasca River at Athabasca Falls	n/a	TP 1980-1993 (166) TN 1980-1993 (166)
Athabasca River below Snaring River	Athabasca River at Jasper	TP 1980-1993 (166) TN 1980-1993 (165)
Athabasca River upstream of Hinton	n/a	TP 1989-1993 (25) TN 1989-1993 (20)
Athabasca River at Obed Coal Bridge	Athabasca River at Hinton	TP 1989-1993 (30) TN 1989-1992 (29)
Athabasca River at Windfall Bridge	n/a	TP 1991-1993 (19) TN 1991-1993 (20)
Athabasca River near Fort Assiniboine	n/a	TP 1989-1993 (32) TN 1989-1993 (25)
Athabasca River near Highway 2 Bridge	n/a	TP 1991-1993 (33) TN 1991-1993 (30)
Athabasca River at the Town of Athabasca	Athabasca River at Athabasca	TP 1980-1992 (150) TN 1987-1992 (62)
Athabasca River 0.1 km upstream of the Horse River	Athabasca River at Fort McMurray minus discharge from the Horse and Clearwater rivers	TP 1989-1992 (23) TN 1989-1992 (22)
Athabasca River at Old Fort	Athabasca River at Fort McMurray plus discharge from downstream tributaries	TP 1988-1992 (56) TN 1988-1992 (39)
Wapiti River near Highway 40	Wapiti River near Grande Prairie	TP 1991-1993 (18) TN 1991-1993 (22)
Wapiti River at mouth	Wapiti River near Grande Prairie plus discharge from Bear River	TP 1991-1993 (24) TN 1991-1993 (23)
Smoky River at Watino	Smoky River at Watino	TP 1980-1992 (150) TN 1987-1992 (53)

Figure 3.1 Discharge and water quality monitoring sites used to calculate nutrient loads for the Athabasca and Wapiti-Smoky Rivers.



Nutrient loads were estimated for each site on the Athabasca and Wapiti-Smoky rivers for which adequate discharge and nutrient data were available (Table 3.1). For every site, data from each year were divided into "intervals" which included one sampling date and the days mid-way between the previous and subsequent sampling dates. The concentration of TP and TN on each sampling date was taken to represent the concentration for each day within the interval. Export for each day was then calculated by multiplying the concentration for that day by the discharge (Environment Canada 1994) for the day. Annual, low-flow and high-flow exports were determined by summing the nutrient export for each interval over a year, December-April and May-November, respectively. Nutrient accrual (the change in nutrient concentration over a known distance for a given year, expressed as mg L^{-1} km^{-1} yr^{-1}) was calculated for the Athabasca River for the reaches between Snaring River and Obed Coal Bridge, Obed Coal bridge and the Town of Athabasca, the Town of Athabasca and Horse River, and Horse River and Old Fort as the change in annual TP or TN export divided by the change in discharge over the reach.

3.2.2 Point-Source Loads

Effluent discharge and TP and TN loads for municipalities with continuous sewage discharge in the Athabasca and Wapiti-Smoky drainage basins are given in Table 2.1. Three communities have discontinuous discharge of sewage lagoons directly to the Athabasca River (Fort Assiniboine, Fort Mackay and Smith). TP and TN data are not available for these communities. However, based on mean TP and TKN values of 3.3 and 12.0 mg/L, respectively, for similar lagoons throughout Alberta (Prince *et al.* 1994) and estimates of water usage of 200 L/person/d (D. Prince, University of Alberta, pers. comm.), we calculated that the TP and TKN loads would be approximately 0.16 and 0.7 tonnes/year, respectively for all three communities combined. These loads are negligible compared to those from continuous sources and we did not include them in future calculations of municipal loading. However, despite their comparatively small loads, inputs from sewage lagoons (which typically discharge in fall and sometimes spring) may have local effects on water quality.

TP and TN loads for pulp mills and other industries within the Athabasca and Wapiti-Smoky drainage basins are given in Tables 2.2 and 2.3. TP and TN loads determined for pulp mills were corrected by subtracting the estimated concentration of the influent water from the effluent concentration. Median concentrations determined for the nearest upstream sampling sites (where available) were used to correct loads for mills.

The percent contribution by municipalities or pulp mills to the nutrient load in the river at any given site was calculated as the sum of all loads from all continuously-discharging municipalities or pulp mills upstream of the site divided by the measured nutrient load (nutrient concentration multiplied by discharge as described in Section 3.2.1) at the site, multiplied by 100. Total anthropogenic contributions for the Athabasca River also included loads from the Athabasca River Suncor Inc. Oil Sands Group for sites located downstream of this discharge. Contributions were not distinguished between those that discharged directly to the mainstem of the Athabasca River (i.e., Jasper, Weldwood of Canada Ltd., Alberta Newsprint Co., Millar Western Pulp Ltd., Whitecourt, Athabasca, Fort McMurray and Athabasca River Suncor Inc. Oil Sands Group) and those that discharged to tributaries (i.e., Edson, Slave Lake, Slave Lake Pulp Corp. and Lac La Biche). Thus, our percent contributions likely overestimate the industrial and municipal load in the river since nutrients from effluents released to tributaries would be taken up or stored, at least in part, in the tributary.

3.3 RESULTS

3.3.1 Athabasca River

Nutrient concentrations varied along the length of the Athabasca River. TP and TN concentrations were lowest upstream of Jasper Townsite in Jasper National Park, increased between Jasper and Hinton and increased again downstream of Hinton (Figure 3.2). On an annual basis, there was little change in median annual TP and TN concentrations from upstream (at Athabasca Falls) to downstream (below Snaring River) of Jasper (from 6 to 10 μg/L TP and 113 to 120 μg/L TN), despite loads of 17 and 79 kg/d TP and TN, respectively, from the Jasper sewage system. Concentrations of TN and TP doubled between the Snaring River and upstream of Hinton sites although there were no point sources of nutrient loading in this reach. Nutrient loads from the combined Weldwood of Canada Ltd. and Town of Hinton outfall (79 and 535 kg/d TP and TN, respectively) were associated with a 33 and 58 % increase in instream TP and TN concentrations, respectively, from upstream of Hinton to the Obed Coal bridge. Thereafter, TN concentrations increased steadily along the river to Fort McMurray. In contrast, TP concentrations returned to background levels 170 km downstream of Hinton, increased below Whitecourt in response to the 138 kg/d load from the Alberta Newsprint Co., Millar Western Pulp Ltd. and the Town of Whitecourt, and then remained relatively constant along the remainder of the river.

Examination of nutrient concentrations versus collection date showed that TP concentrations were consistently lower during low flows (December-April) whereas during high flows (May-November), concentrations were highly variable (Figure 3.3). Seasonal patterns in TN were less well defined although TN concentrations at some sites (Athabasca River at Snaring River and at Athabasca) appeared lower during fall (Figure 3.4). As a result, longitudinal patterns in long-term TN concentrations showed little difference between low and high flow seasons, whereas median TP concentrations were greater during high flows for all sites except at Fort Assiniboine (Figure 3.5).

Of the 721 TP measurements from Athabasca River between 1980-1993, 146 measurements or 20% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) guideline for TP of 0.05 mg/L P (Table 3.2). The majority of these exceedances (79%) occurred during the higher-flow period between May and November with only 21% between the lower-flow period of December-April. The fact that fewer exceedances occurred during low flows when effluent dilution would be lowest, that most exceedances occurred at or below the Town of Athabasca (where, for these pre-1993 data, there were no pulp mills) and that the percent of exceedances is similar upstream and downstream of Hinton suggests that effluent inputs are not the major cause of TP exceedances. TP exceedances are likely due to transport of particulate P during periods of high discharge. The *Alberta*

Figure 3.2 Total phosphorus (TP) and total nitrogen (TN) concentrations (median, 25th and 75th percentiles for all years) in the Athabasca River, Alberta calculated from annual data. (Data described in Table 3.1 and tabulated in Appendix C.)

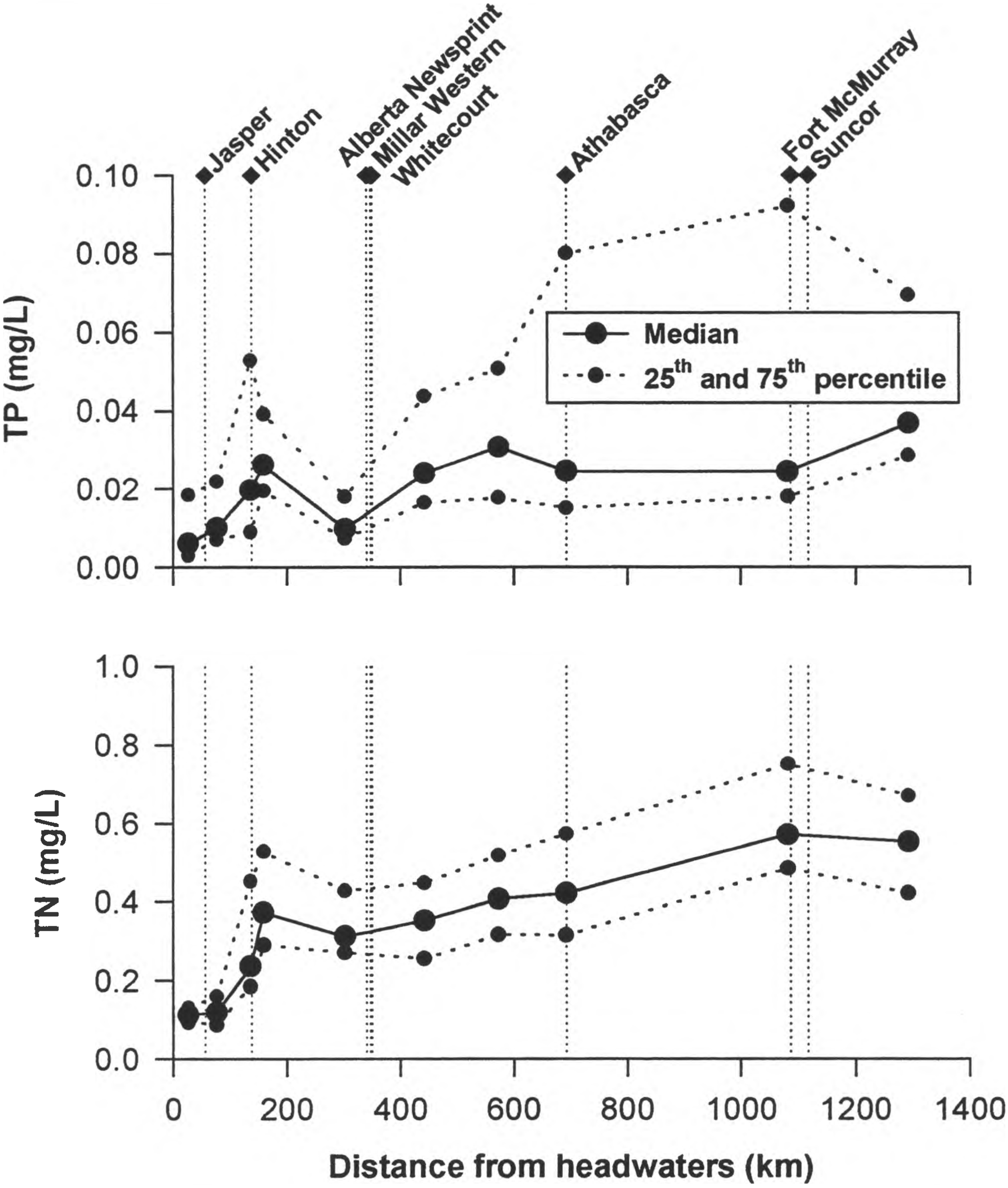


Figure 3.3 Total phosphorus (TP) concentrations in relation to time of year for the Athabasca River, Alberta: (a) at Athabasca Falls, (b) downstream of Snaring River confluence, (c) upstream of Hinton, (d) Obed Coal bridge, (e) at Fort Assiniboine, (f) at Athabasca, (g) 0.1 km upstream of the Horse River confluence, and (h) at Old Fort. Dashed line is the *Alberta Surface Water Quality objective* for TP of 0.05 mg/L P.

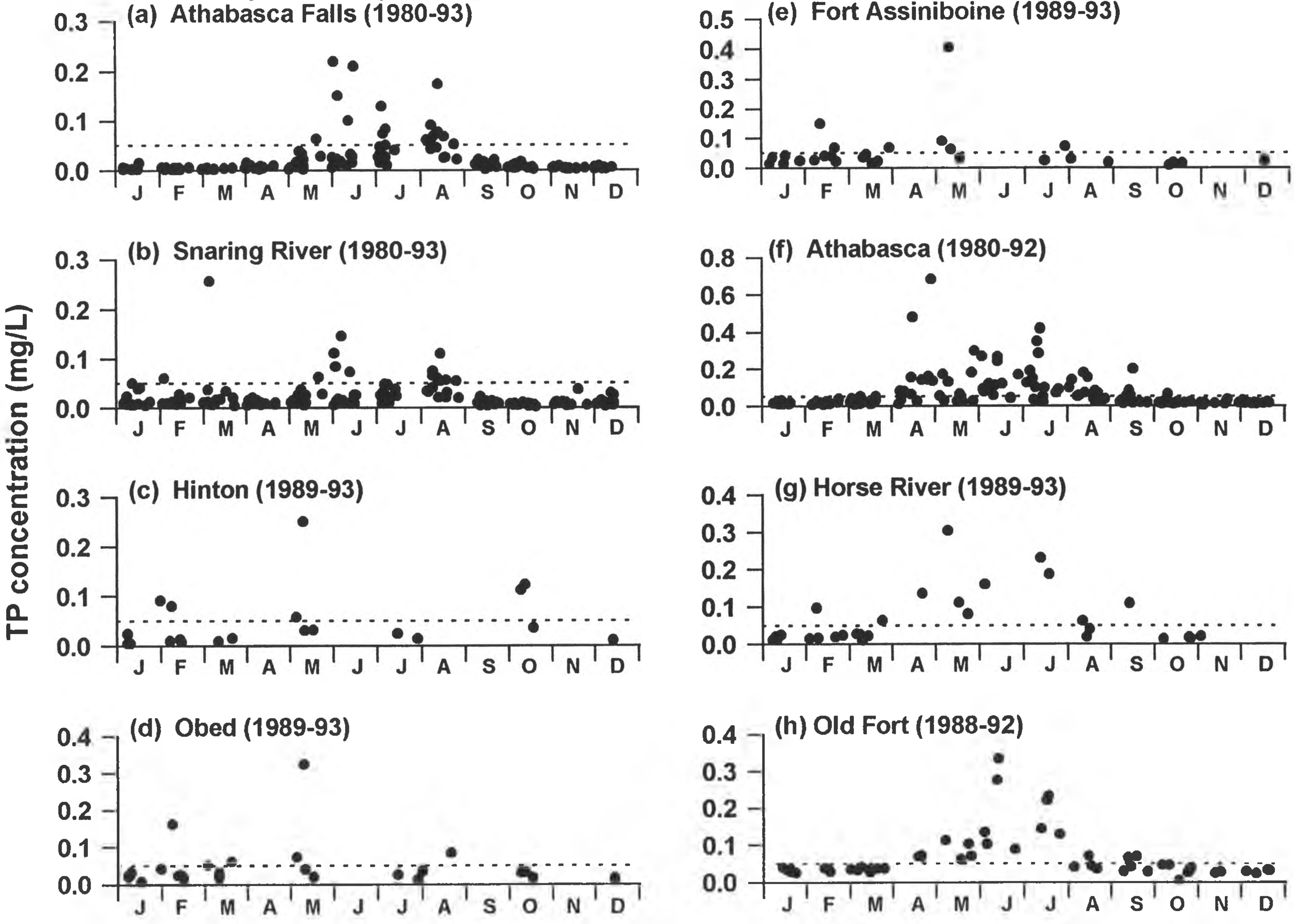


Figure 3.4 Total nitrogen (TN) concentrations in relation to time of year for the Athabasca River, Alberta: (a) at Athabasca Falls, (b) downstream of Snaring River confluence, (c) upstream of Hinton, (d) Obed Coal bridge, (e) at Fort Assiniboine, (f) at Athabasca, (g) 0.1 km upstream of the Horse River confluence, and (h) at Old Fort. Dashed line is the *Alberta Surface Water Quality objective* for TN of 1.0 mg/L N.

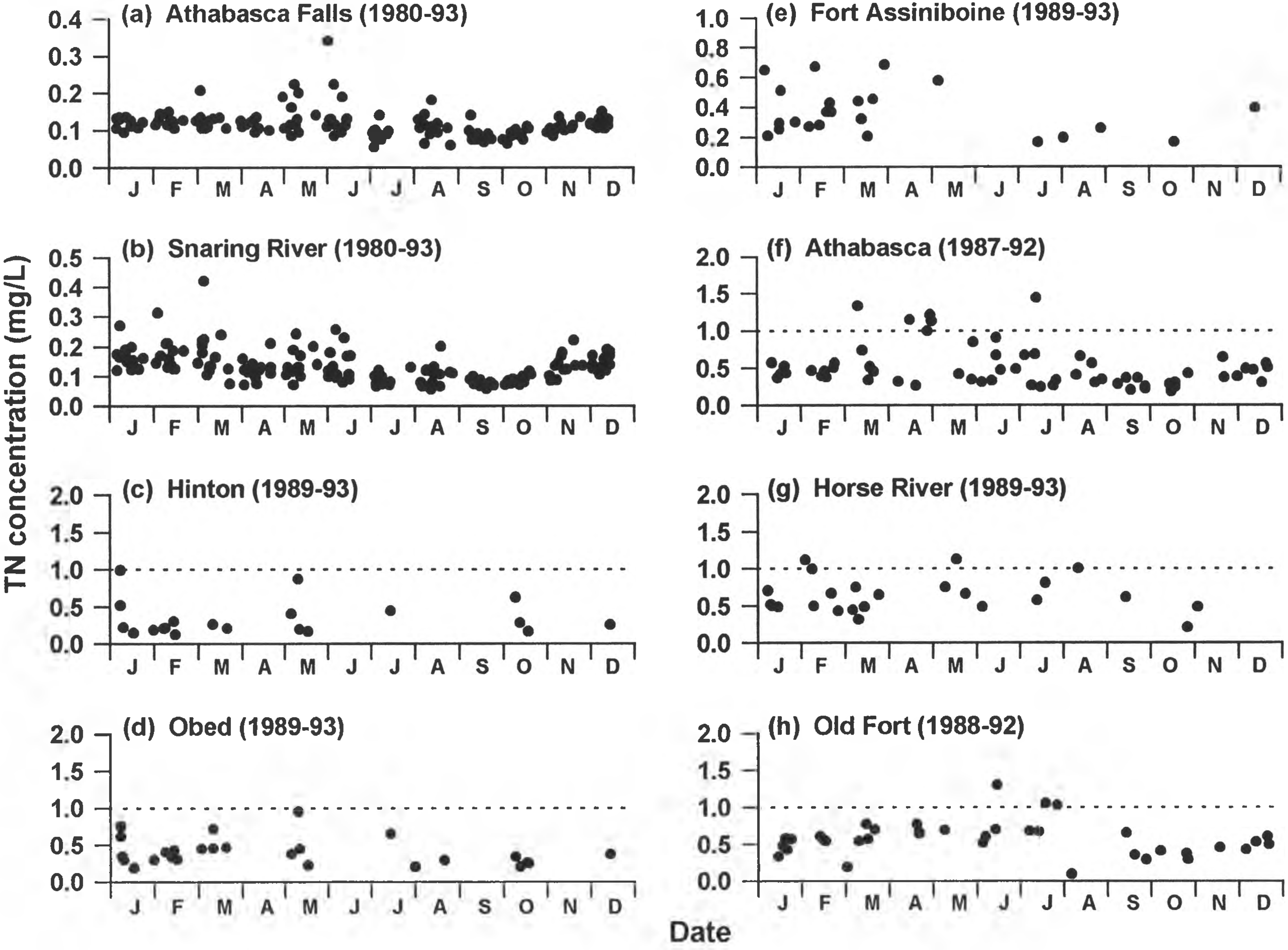


Figure 3.5 Total phosphorus (TP) and total nitrogen (TN) concentrations (median, 25th and 75th percentiles) in the Athabasca River, Alberta calculated for low (December - April) and high (May - November) flow seasons. (Data described in Table 3.1 and tabulated in Appendix C.)

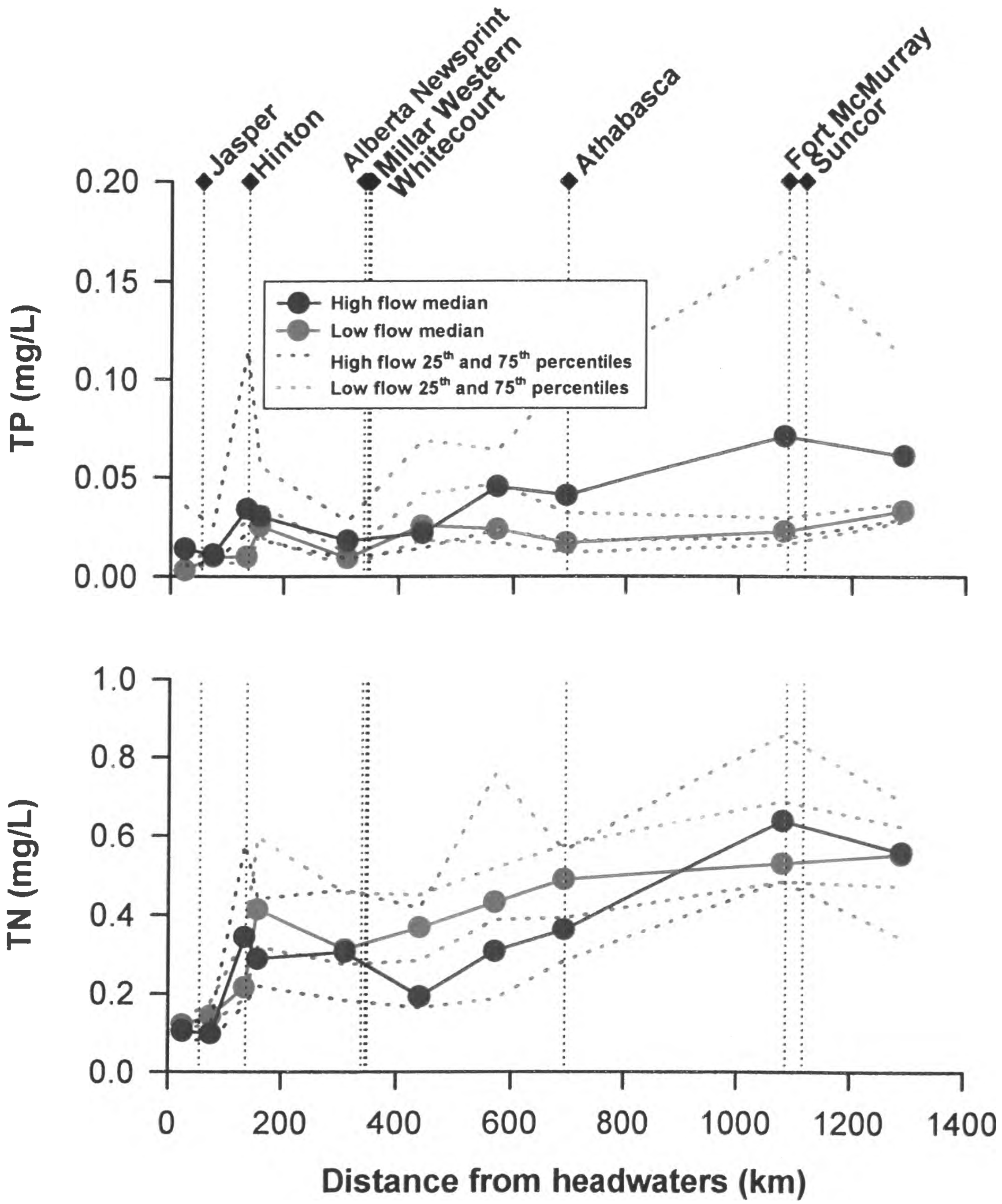


Table 3.2 Summary statistics for total nitrogen (TN) and total phosphorus (TP) concentrations from longer-term monitoring sites on the Athabasca, Wapiti and Smoky rivers and number of values exceeding the *Alberta Surface Water Quality Objectives* (Alberta Environment 1977) of 0.05 mg/L TP as P and 1.0 mg/L TN as N.

Site	Years	TN (mg/L)					TP (mg/L)				
		Median	Max	Min	n	# exceedances	Median	Max	Min	n	# exceedances
Athabasca @ Athabasca Falls	1980-93	0.113	0.71	0.55	166	0	0.006	0.22	0.002	166	18
Athabasca below Snaring R.	1980-93	0.12	0.42	0.055	165	0	0.01	0.256	0.002	166	14
Athabasca u/s of Hinton	1989-93	0.236	0.99	0.122	22	0	0.0197	0.25	0.0049	24	6
Athabasca @ Obed Coal Br.	1989-93	0.373	1.384	0.184	29	1	0.0262	0.323	0.007	30	6
Athabasca @ Windfall Br.	1991-93	0.3125	0.61	0.145	18	0	0.0097	0.312	0.005	19	1
Athabasca near Ft. Assiniboine	1989-93	0.353	0.686	0.164	25	0	0.024	0.405	0.007	32	7
Athabasca @ Hwy. 2 Br.	1991-93	0.4075	0.964	0.1	30	0	0.0308	0.114	0.009	33	8
Athabasca @ Athabasca	1980-93 (TP) 1987-93 (TN)	0.422	1.444	0.183	71	5	0.0245	0.682	0.004	163	56
Athabasca 0.1 km u/s Horse R.	1989-92	0.571	1.124	0.203	27	3	0.0244	0.304	0.01	32	11
Athabasca @ Old Fort	1988-92	0.553	1.295	0.09	39	3	0.0368	0.332	0.004	56	19
Smoky R. @ Watino	1980-92 (TP) 1987-92 (TN)	0.48	2.134	0.124	53	7	0.0415	1.05	0.0053	150	67
Wapiti R. @ Hwy. 40	1991-93	0.289	0.69	0.141	21	0	0.0098	0.138	0.0028	25	3
Wapiti R. @ mouth	1991-93	0.7465	1.454	0.049	26	5	0.0689	0.21	0.0222	27	20

Surface Water Quality Objective (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by only 2% of the samples (Table 3.1).

TP export for the Athabasca River increased from 80 tonnes/y near the headwaters (Athabasca River below Snaring River) to 2311 tonnes/y at Old Fort, with 94% of the TP export occurring during the high flow season (Figure 3.6). Nitrogen export also increased along the river with annual TN export increasing from 298 tonnes/y near the headwaters (Athabasca River below Snaring River) to 13670 tonnes/y at Old Fort (Figure 3.6). As with TP, most (87%) TN export occurred during the May-November high flow season (Figure 3.6). While these large downstream increases in nutrient export are primarily due to concurrent increase in discharge (and not increases in concentration), determinations of nutrient accrual (the change in annual export divided by the change in discharge along a reach divided by river distance) indicate that the four river reaches accrue nutrients at different rates (Figure 3.7). The Snaring River to Obed reach had the greatest TN accrual rate (7.5 $mg/m^3/km/y$ TN); it also received the largest point-source TN load (572 kg/d). TP accrual rates were also greatest in the Snaring River to Obed reach (0.53 $mg/m^3/km/y$ TP) followed by the Athabasca to Horse River reach (0.48 $mg/m^3/km/y$ TP) despite point-source loading of TP to the Athabasca River mainstem being greatest in the Obed to Athabasca reach.

Using pre-1994 data, continuously-discharging industrial and municipal sources contributed 6 to 16% of the TP export (tonnes/year) in the Athabasca River on an annual basis (Figure 3.8). With the exception of Jasper, < 3% of the annual TP load was attributable to municipal sources. However, during low flows, 37% of the TP load at Old Fort was from continuously-discharging industrial and municipal sources (27% from pulp mill sources and 10% from municipal sources) while downstream of Hinton at the Obed Coal bridge, the Hinton combined effluent contributed 61% of the TP load during low flow seasons. The only major municipal contributor to TP loads in the Athabasca River was the Town of Jasper which contributed 90% of the TP load at the Snaring River site during low flow. While the TP load from Jasper sewage is similar to that of other towns on the Athabasca River (Table 2.1), it represents a substantial contribution because of the very low TP concentrations upstream of Jasper during low flow conditions (6 μg/L TP median value). With respect to TN, continuously-discharging industrial and municipal sources contributed 4 to 10% of the TN load in the Athabasca River on an annual basis, with < 2% attributable to all municipalities except Jasper which contributed approximately 10% of the TN load at the Snaring River site (Figure 3.8). However, during low flows, 42% of the TN load downstream of Jasper at Snaring River was due to sewage while 39% of the TN load at the Obed Coal bridge was due to the combined Weldwood of Canada Ltd. and Hinton effluent.

The above assessments of nutrient loading in the Athabasca River do not consider the effect of the AlPac pulp mill which started operations in September 1993. Sufficient data are not available to statistically assess changes in TP and TN loads in the Athabasca River in relation to loading from the AlPac pulp mill. Comparison of 1994 nutrient concentrations for the Athabasca River at Athabasca (6 km upstream of AlPac discharge), Athabasca River at Calling River (73 km downstream of the AlPac discharge) and Athabasca River 0.1 km upstream of the Horse River (383 km downstream of the AlPac discharge) suggests that there have been no adverse changes in TP and TN concentrations at these near (73 km

Figure 3.6 Total phosphorus (TP) and total nitrogen (TN) loads for the Athabasca, Wapiti and Smoky rivers, Alberta calculated for annual data and for low (December-April) and high (May-November) flow seasons. (Data described in Table 3.1 and tabulated in Appendix C.)

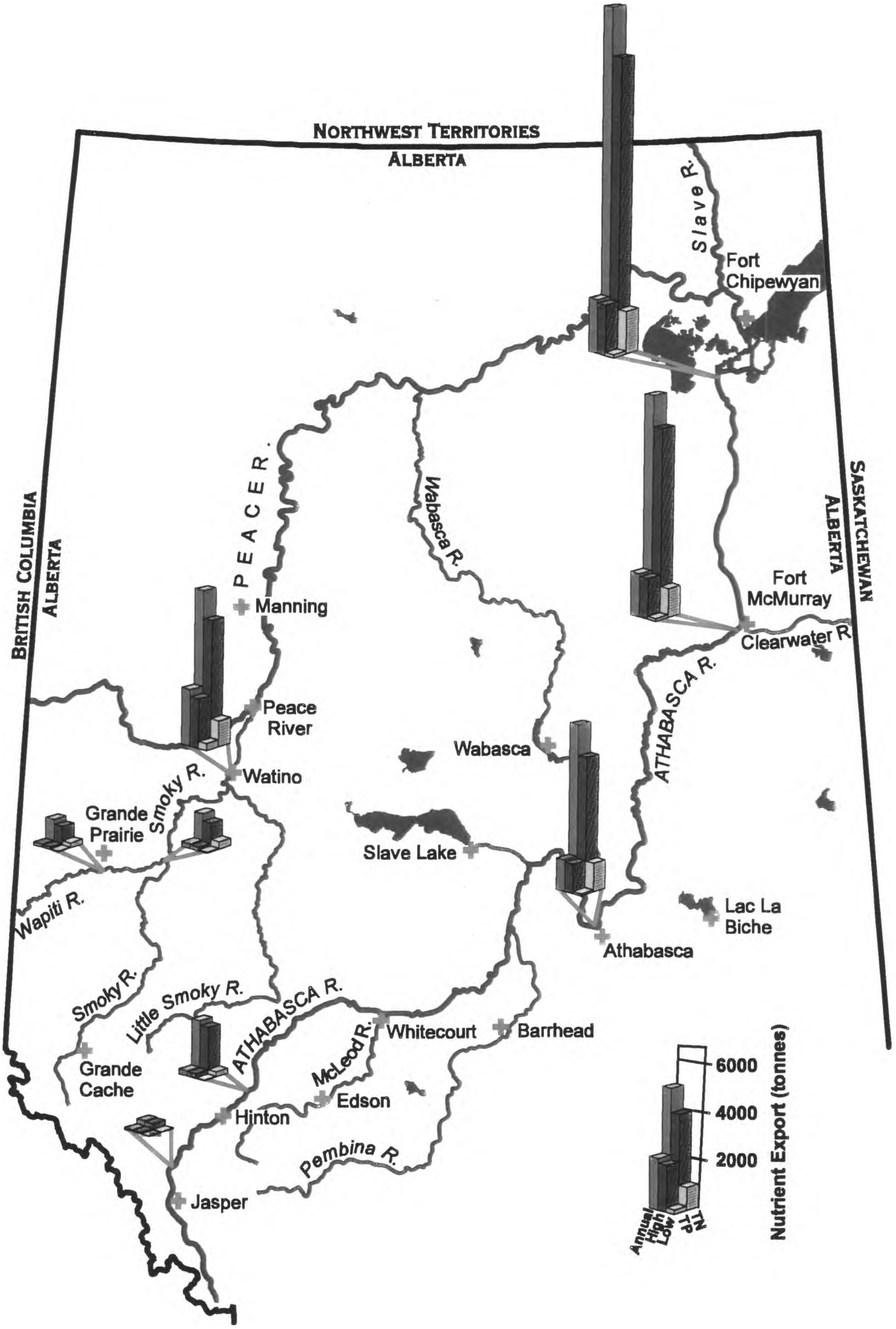


Figure 3.7 Total phosphorus (TP) and total nitrogen (TN) accrual rates for the Athabasca River, Alberta between Snaring River and Obed Coal bridge (Section I), Obed Coal bridge and Athabasca (Section II), Athabasca and Horse River (Section III), and Horse River and Old Fort (Section IV).

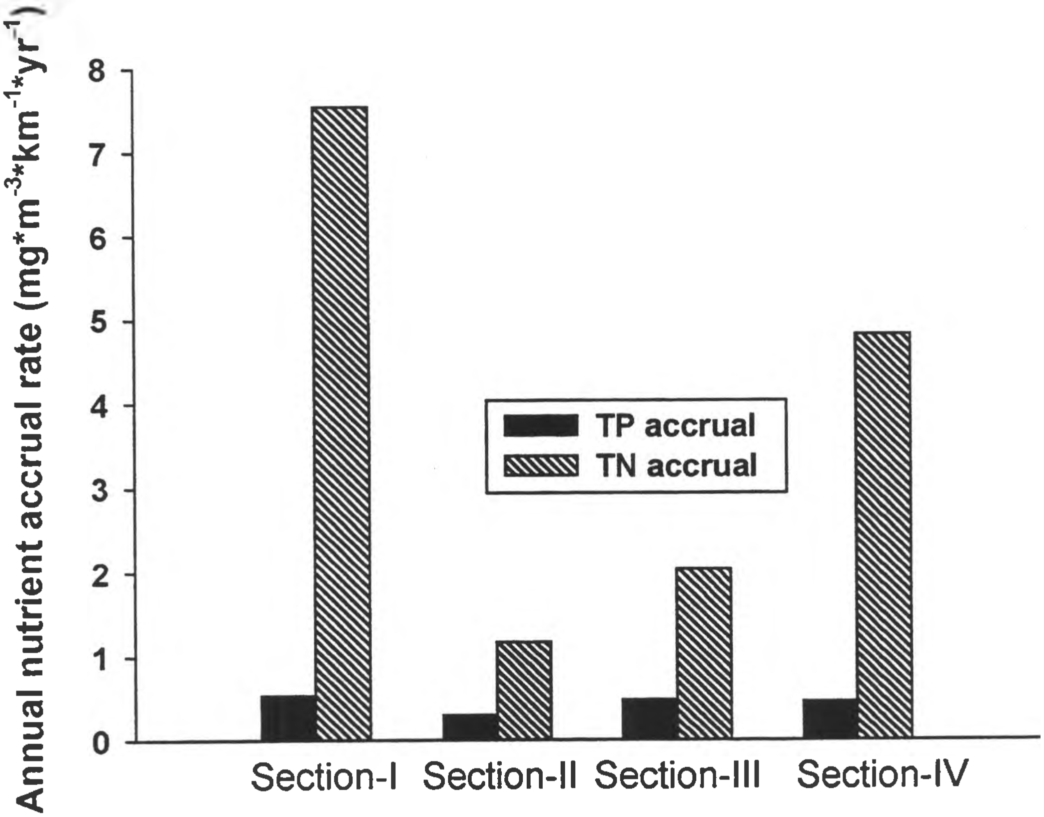
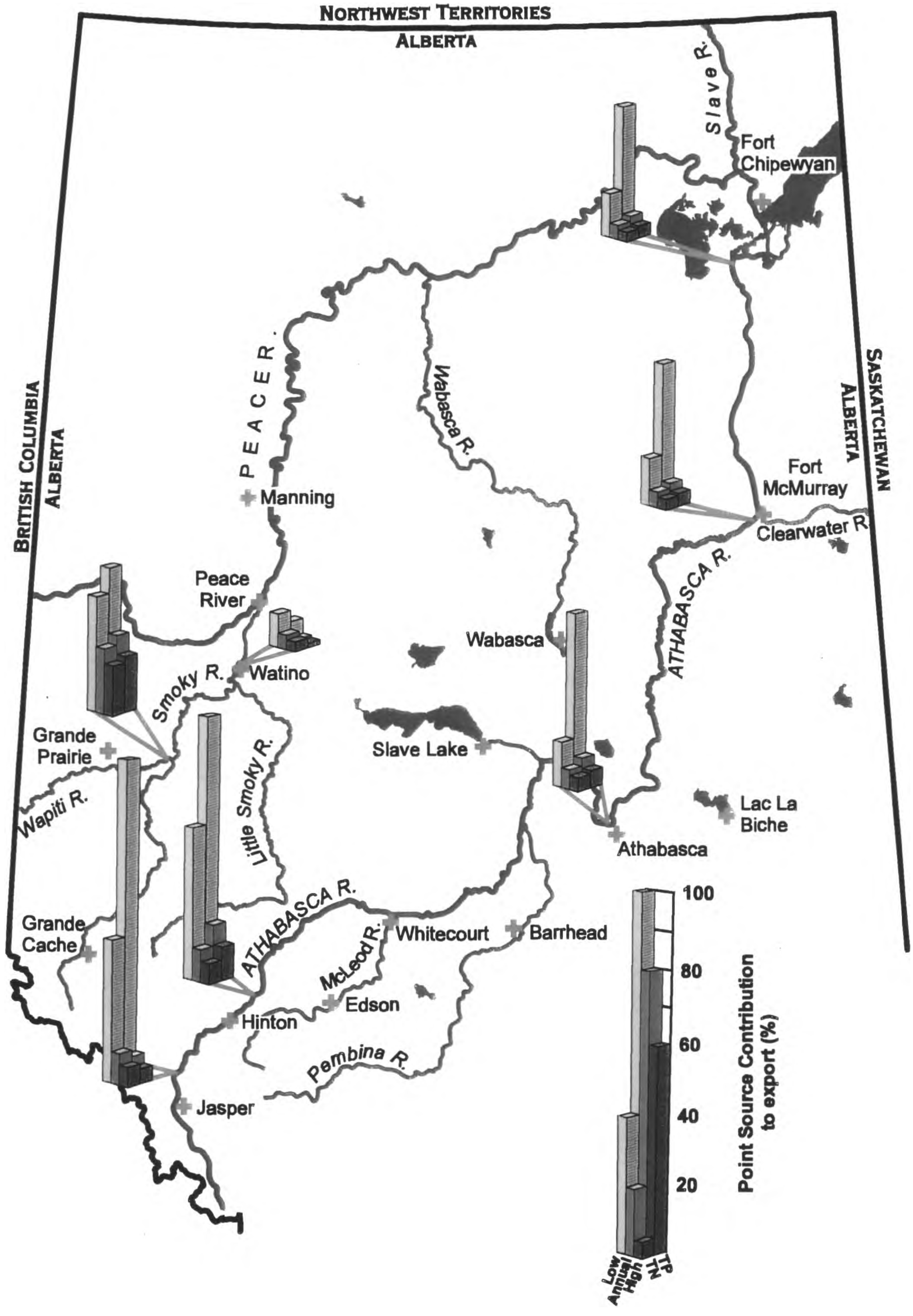


Figure 3.8 Point-source contributions to total phosphorus (TP) and total nitrogen (TN) export for the Athabasca, Wapiti and Smoky rivers, Alberta calculated for annual data and for low (December - April) and high (May - November) flow seasons. (Data summarized in Table 3.1 and tabulated in Appendix C.)



downstream) and far-field (383 km downstream) sites as a result of the start-up of the AlPac mill (Figure 3.9).

3.3.2 Wapiti-Smoky Rivers

Year-round chemistry data for the Wapiti-Smoky rivers are limited to three sites. On an annual basis, TN and TP concentrations increased along the Wapiti River from upstream of Grande Prairie to the river mouth; concentrations were lower in the Smoky River at Watino than at the mouth of the Wapiti River (Figure 3.10). During high flows, TP and TN concentrations increased along the Wapiti River and then showed either a small increase (TP) or no change (TN) for the Smoky River at Watino (Figure 3.11). Examination of nutrient concentrations versus collection date showed that TP concentrations were higher during low flows (January-April) and lower during high flows (May-November) (Figure 3.12). There was little, if any, seasonal variability in long-term TN concentrations (Figure 3.12).

Of the 202 TP measurements for the Wapiti-Smoky system, 90 measurements or 45% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP of 0.05 mg/L P, with the site of greatest percent of exceedances being the Wapiti River at the mouth (Table 3.2). The fact that the percent of exceedances increased from 12 to 74% from upstream of Grande Prairie to the mouth of the Wapiti River indicates that P from the City of Grande Prairie and Weyerhaeuser Canada Ltd. effluents contributed to non-compliance with the TP objective. The *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by 12% of the samples and the observation that all samples from upstream of Grande Prairie were below the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN while 5 of 26 samples from the Wapiti River at the mouth exceeded the objective indicates that the Grande Prairie pulp mill and, to a lesser extent, sewage discharge contribute to exceedances.

TP export for the Wapiti-Smoky river increased slightly from 125 tonnes/y near the headwaters (Wapiti River at highway 40) to 204 tonnes/y at the mouth of the Wapiti River, and then increased to 2442 tonnes/y for the Smoky River at Watino (Figure 3.6). Nitrogen export showed a similar pattern and increased only slightly along the Wapiti River (from 1018 to 1335 tonnes/y) and then increased to 6421 tonnes/y at Watino (Figure 3.6). Most of the TP and TN export at Watino (88 and 82%) occurred during the May-November high flow season. The Smoky River increase in nutrient export is primarily due to an increase in discharge (and not an increase in concentration).

On an annual basis, continuously-discharging industrial and municipal sources contributed 22% of the TP load in the Wapiti River (13% from the pulp mill and 10% from Grande Prairie) (Figure 3.8). However, during low flows, 41% of the TP load of the Wapiti River was from continuously-discharging industrial and municipal sources (24% from the pulp mill and 18% from Grande Prairie). The point-source contribution to TP export for the Smoky River at Watino was 2% on an annual basis and less than 7% during the low flow period.

Figure 3.9 Long-term (1989-1992; mean±S.E.) and 1994 total phosphorus (TP) and total nitrogen (TN) concentrations at sites 6 km upstream (Athabasca River at Athabasca), 73 km downstream (Athabasca River at Calling River) and 383 km downstream (Athabasca River 0.1 km upstream of the Horse River) of the Alberta Pacific Forest Industries Ltd. (AlPac) effluent outfall.

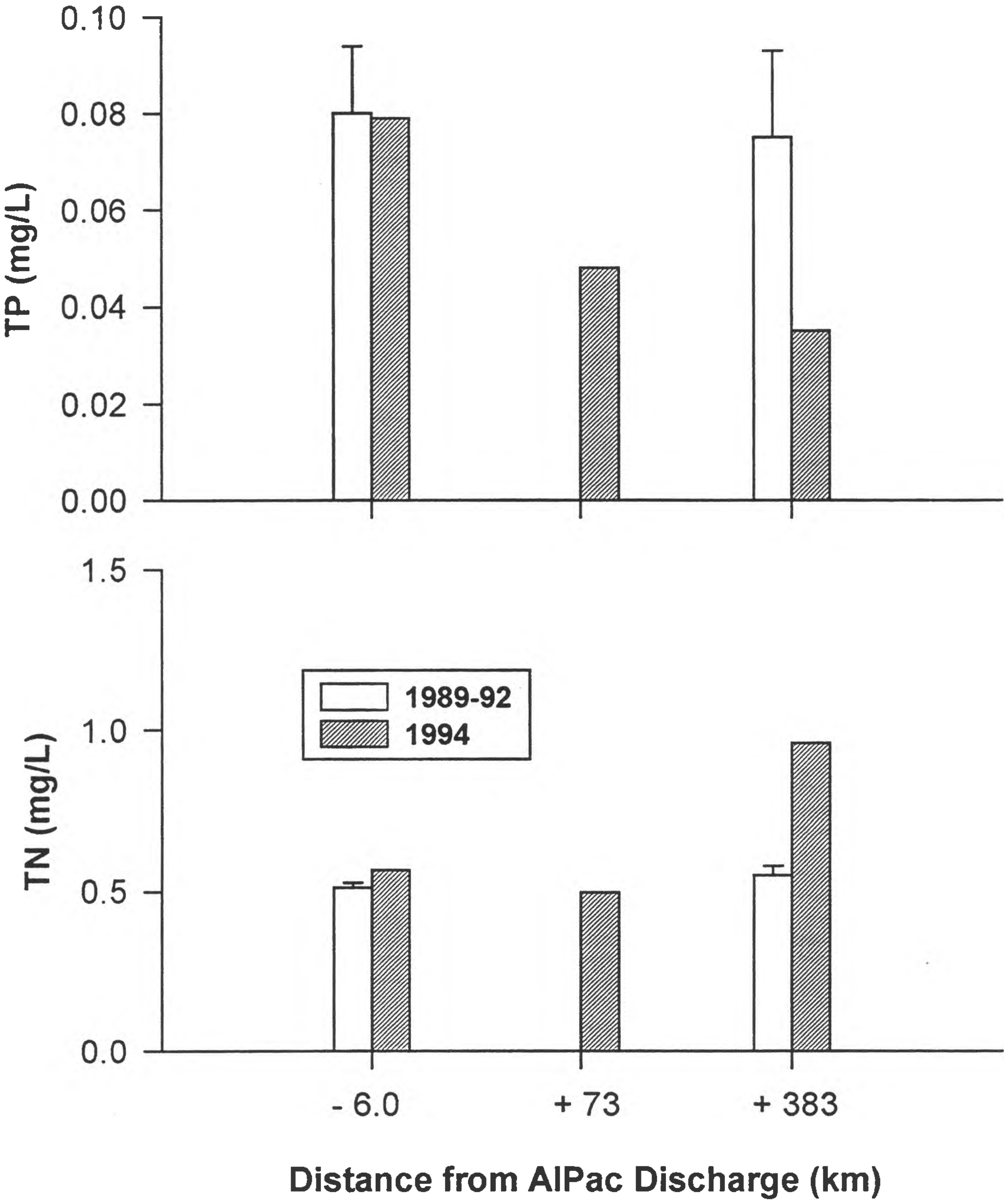


Figure 3.10 Total phosphorus (TP) and total nitrogen (TN) concentrations (median, 25th and 75th percentiles) for the Wapiti-Smoky river, Alberta calculated for annual data. (Data described in Table 3.1 and tabulated in Appendix C.)

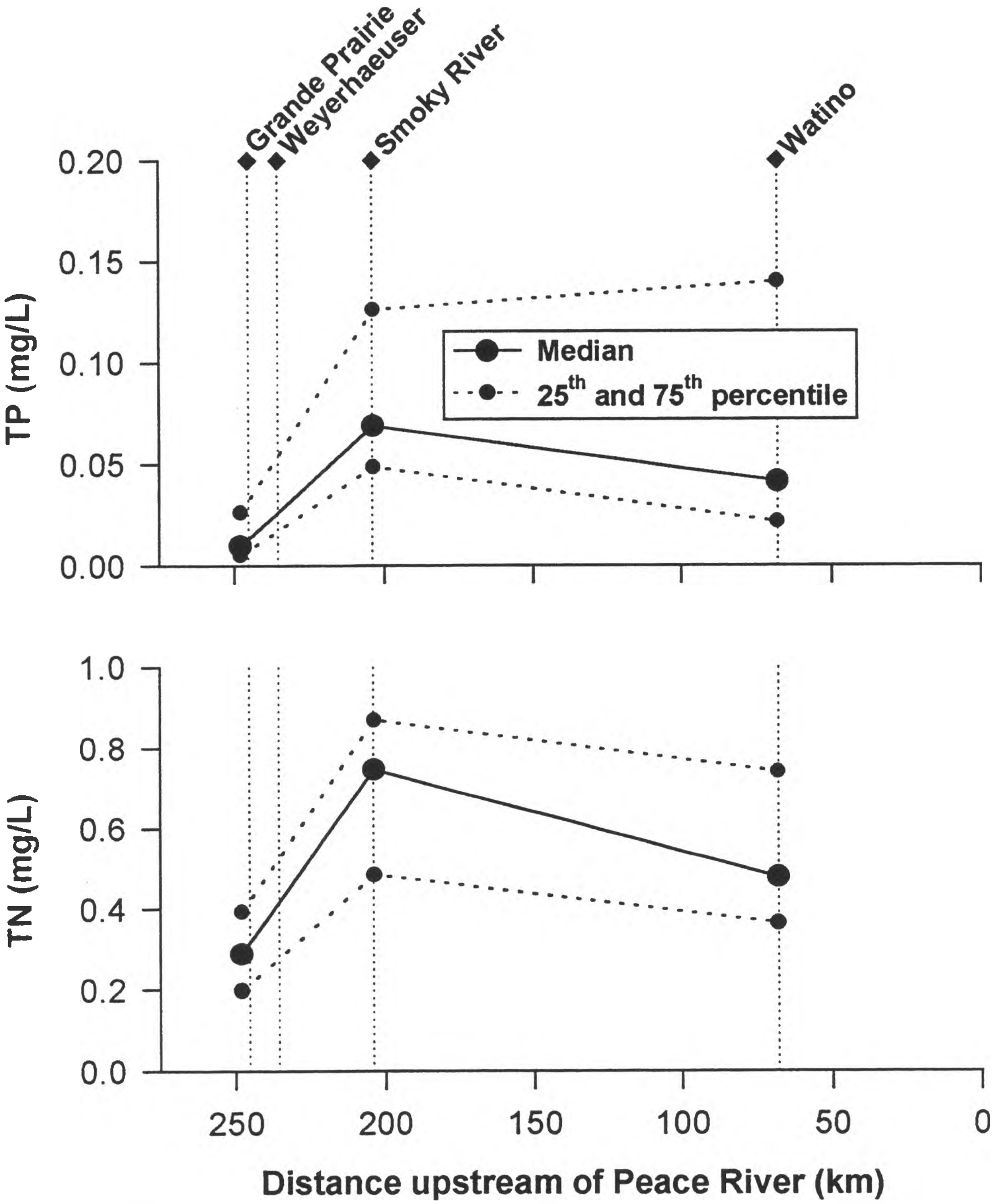


Figure 3.11 Total phosphorus (TP) and total nitrogen (TN) concentrations (median, 25th and 75th percentiles for all years) for Wapiti-Smoky river, Alberta calculated for low (December - April) and high (May- November) flow seasons. (Data described in Table 3.1 and tabulated in Appendix C.)

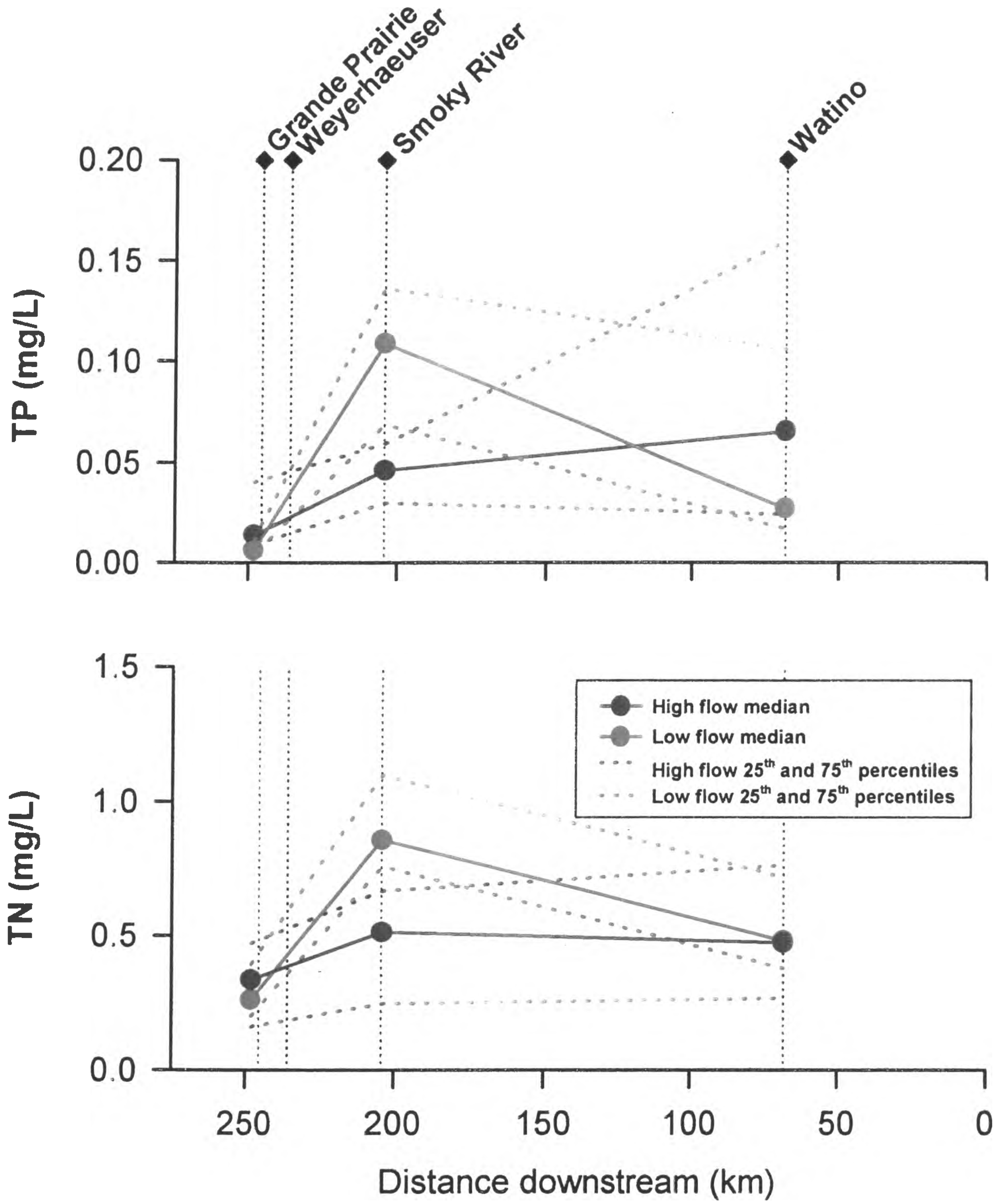
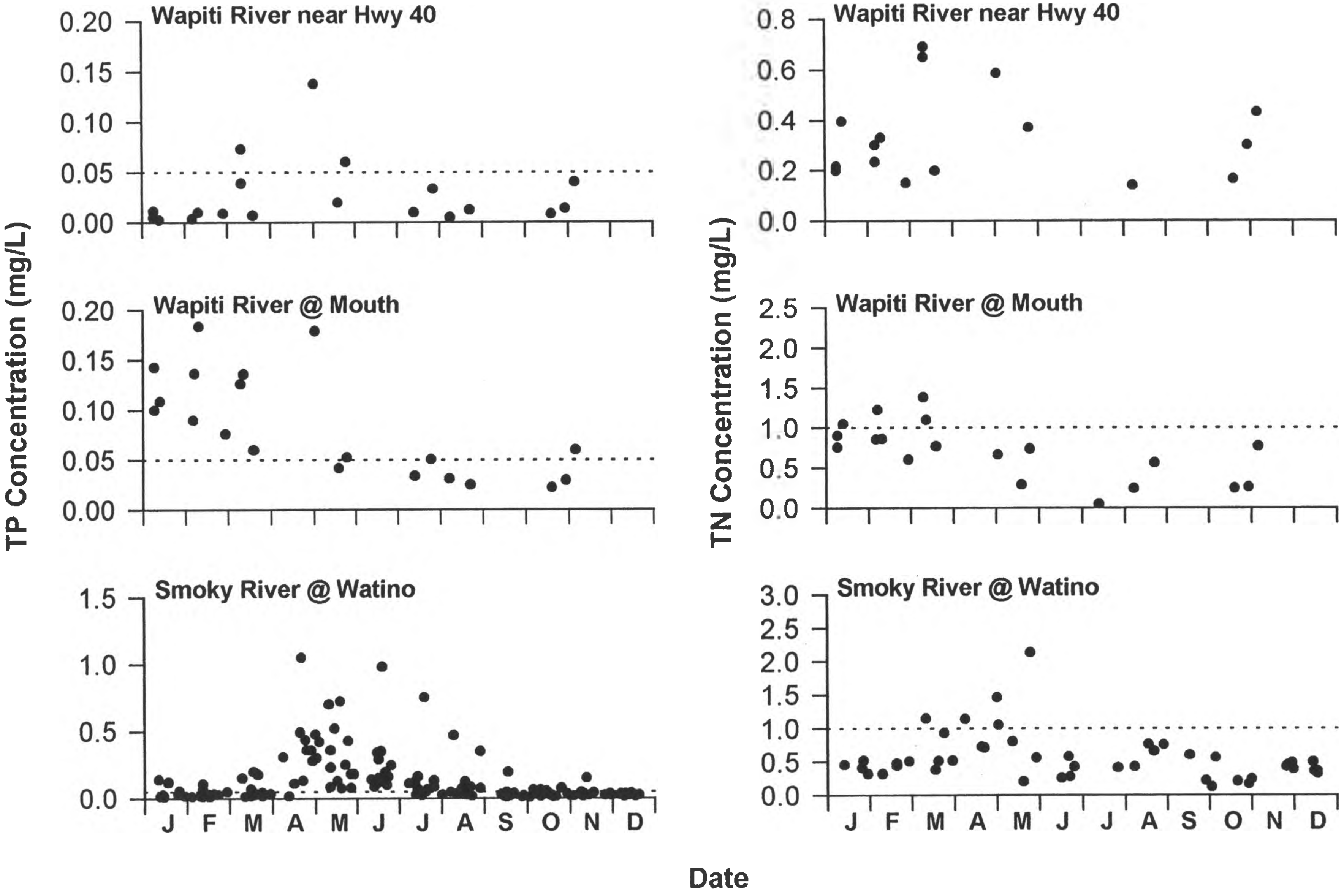


Figure 3.12 Total phosphorus (TP) and total nitrogen (TN) concentrations in the Wapiti-Smoky river, Alberta in relation to time of year for the: (a) Wapiti River at highway 40, (b) Wapiti River near the mouth, and (c) Smoky River at Watino.



With respect to TN, anthropogenic point sources contributed 20% of the TN load in the Wapiti River on an annual basis (13% from the pulp mill and 7% from Grande Prairie) (Figure 3.8). However, during low flows, 34% of the TN load of the Wapiti River was due to continuously-discharging point sources (22% from the pulp mill and 12% from Grande Prairie). TN export for the Smoky River at Watino was 6421 tonnes/y with 3% attributable to Weyerhaeuser Canada Ltd. and 2% to the Grande Prairie and Grande Cache sewage effluents.

3.4 DISCUSSION

Nutrient concentrations varied along the length of the Athabasca and Wapiti-Smoky rivers. In the Athabasca River, TP and TN concentrations were lowest upstream of the Town of Jasper and increased between Jasper and Hinton and, again, downstream of Hinton. On an annual basis, TP concentrations were consistently lower during low flows (December-April) whereas during high flows (May-November), concentrations were highly variable. There was less evidence of seasonal variability in long-term TN concentrations. As a result, longitudinal patterns in long-term TP and TN concentrations showed little difference between low and high flow seasons, except for TP concentrations downstream of Smith which were consistently higher during high flows. Of the 721 TP measurements from the Athabasca River between 1980-1993, 146 measurements or 20% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP of 0.05 mg/L P. Most of these exceedances occurred during summer and were likely due to high particulate P concentrations. TN concentrations in the Athabasca River are lowest around Jasper and typically increase downstream of Hinton and thereafter increase steadily along the remaining length of the river. The *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by only 2% of the samples.

For the Wapiti-Smoky river, TN and TP concentrations generally increased along the Wapiti River but were lower in the Smoky River at Watino than at the mouth of the Wapiti River during high flows. Of the 27 TP measurements at the mouth of the Wapiti River, 20 measurements or 74% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP of 0.05 mg/L P. The fact that the percent of exceedances increased from 12 to 74% from upstream of Grande Prairie to the mouth of the Wapiti River suggests that P from the City of Grande Prairie and Weyerhaeuser Canada Ltd. effluents contributed to non-compliance with the TP guideline. The *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by 19% (n=26) of the samples from the Wapiti River near the mouth compared to no TN exceedances (n=21) for samples from upstream of Grande Prairie, again suggesting that exceedances are related to nutrient loading from the Grande Prairie STP and mill.

Exceedances of *Alberta Surface Water Quality Objectives* (Alberta Environment 1977) have also been routinely observed in other rivers in the province. From 1970-1980, TP and TN concentrations in the Bow River were consistently low downstream of Calgary but regularly exceeded guidelines for over 300 km downstream of Calgary in the case of TP and over 80 km downstream for TN (Hamilton and North 1986). These exceedances of nutrient guidelines served in part for the decision to upgrade Calgary's two

STP's in 1982-83. While TP and TN concentrations have decreased downstream of Calgary since the STP upgrades, concentrations still frequently exceed *Alberta Surface Water Quality Objectives* (Alberta Environment 1977) (Sosiak 1990). In the North Saskatchewan River between 1982-1984, 20 to 30% of samples from upstream and > 85% of samples from downstream of Edmonton exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP (Anderson *et al.* 1986). Most of the TP was particulate and unlikely to be biologically available (Anderson *et al.* 1986 after McNeely *et al.* 1979). TN exceedances in the North Saskatchewan River occurred less frequently and were usually limited to downstream of major effluent outfalls (Anderson *et al.* 1986). It should be noted that *Alberta Surface Water Quality Objectives* (Alberta Environment 1977) are not legal statutes; only limits as given in effluent discharge licenses are recognized as enforceable environmental control laws by the provincial government.

TP export for the Athabasca River increased from 80 tonnes/y near the headwaters (Athabasca River below Snaring River) to 2311 tonnes/y at Old Fort with most (94%) of the export occurring during the May-November high flow season. We estimated that pulp mills and municipalities contributed 27 and 10% of the TP load, respectively, at Old Fort during low flows compared to 3 and 0.9%, respectively, during high flows. These values are similar to the Alberta Environmental Protection (1995a) calculations of 36 and 8% TP contributions for pulp mills and municipalities, respectively, during winter and 8 and 2%, respectively, during summer given that we divided the year into two hydrologic periods (i.e., high versus low flows) whereas the provincial calculations were based on four seasons. (Any discrepancies between the Alberta Environmental Protection (1995a) and our calculations are solely due to differences in the time period over which the data were compared (i.e., high and low flows periods for this report versus summer (May-September) and winter (December-March) for the provincial report as both sets of calculations were based on the same data). The largest municipal contributor of N and P to the Athabasca River was Jasper Townsite which contributed 5% of the TP and 6% of the TN load during high flows but 90% of the TP and 42% of the TN load during low flow. In an analysis of water quality in Jasper National Park for July - October 1976, Gummer and Block (1978) likewise noted that Jasper effluent had little effect on TP and TN concentrations during the high flow period. However, during low flows, when TP concentrations upstream of Jasper decreased from the high flow median of 14 μg/L to 3 μg/L, we found that the proportional contribution of Jasper sewage to the river's nutrient load was much greater.

For the Smoky River at Watino, 4 and 3% of the TP load is attributable to pulp mills and municipalities, respectively, during low flows compared to 0.7 and 0.6%, respectively, during high flows. This is less than the 20% (11% from pulp mill and 9% from municipal sources) reported by Alberta Environmental Protection (1995a) for the Wapiti-Smoky basin during winter, although our high-flow estimates are similar to the provincial calculations for summer (i.e., 1% each for pulp mill and municipal sources; Alberta Environmental Protection (1995a)).

Industrial and municipal contributions to nutrient export have been evaluated for other watersheds in Canada and throughout the world (Table 3.3). For the Fraser River, British Columbia, 13% of the TP export at Marguerite during the low flow season is from anthropogenic point sources (11% from pulp mill and 2% from municipal sources) as compared to 5% (4% from pulp mill and 1% from municipal

Table 3.3 Total phosphorus (TP) and total nitrogen (TN) export from rivers throughout the world and the percent contribution from point sources to these exports.

River and Site	Drainage Area (km^2)	Mean Annual Discharge (m^3/s)	TP		TN		References
			Export (tonnes/y)	% Point Sources	Export (tonnes/y)	% Point Sources	
Athabasca, Canada at Snaring River at Obed Coal at Athabasca at Horse River at Old Fort	 3880 9780 74600 133000 155000	 86 186 417 503 650	 80 219 1361 1866 2311	 7.7 16.1 8.4 6.3 5.7	 298 2254 6816 8980 13670	 9.6 9.9 6.0 4.8 4.2	this report; drainage areas for Snaring River, Obed Coal, Horse River and Old Fort are for nearest gauging station (Jasper, Hinton, Fort McMurray, Athabasca and Embarras, respectively)
Fraser, Canada at Red Pass at Hansard at Marguerite at Hope	 1700 18000 114000 217000	 14 444 1315 2684	 7 1076 5772 10337	 0.0 0.0 6.6 4.4	 n/a n/a n/a n/a	 n/a n/a n/a n/a	French and Chambers (1995)
Flint, Ga, USA	n/a	n/a	n/a	< 5	n/a	< 5	Byrd *et al.* (1986)
Girou, France	520	< 5	11.5	60.8	n/a	n/a	Probst (1985)
Main, Germany at Kostheim	21505[1]	212[2]	5800	51.7	54000	48.1	chemistry data from Behrendt (1993); [1]Van der Leeden (1975) at Kleinhaubach; [2]Van der Weijden and Middleburg (1989)
Mosel, Germany at Koblenz	27100[1]	367[2]	5300	34.0	56000	21.4	chemistry data from Behrendt (1993); [1]Van der Leeden (1975) at Cochem; [2]Van der Weijden and Middleburg
Neckar, Germany at Mannheim	n/a	161[1]	3100	74.2	34000	61.8	chemistry data from Behrendt (1993); [1]Van der Weijden and Middleburg (1989)
Rhine, Germany at Koblenz at Lobith	 103730[1] 160000[1]	 1560[1] 2200[2]	 24500 35400	 56.3 63.6	 216000 505000	 42.1 51.9	chemistry data from Behrendt (1993); [1]Van der Leeden (1975); [2]Van der Weijden and Middleburg (1989)
Smoky, Canada at Watino	50352	323	2442	2.0	6421	4.3	this report
Vistula, Poland at Kiezmark	194414[1]	1010[2]	2323 (for 6 mon.)[1]	~30[3]	29904 (for 6 mon.)[1]	~30[3]	[1]Sundblad *et al.* (1994); [2]Van der Leeden (1975); [3]Sundblad *et al.* (1994 after Rybinski *et al.* 1990)
Wapiti, Canada at mouth	14468	74	204	22.4	1335	19.6	this report

sources) during high flows (French and Chambers 1995). Byrd *et al.* (1986) noted that the Flint River pulp mill near Oglethorpe, Georgia, USA contributed ≤5% of the N and P in the Flint River. In Scandinavia, 10% of the TP load to the Gulf of Bothnia was from the pulp and paper industry with 14 and 2% from sewage and other industries, respectively (Enell and Haglind 1994). Wartiovaara and Heinonen (1991) noted that in Finland, the relative contribution to TP loading from sewage versus the pulp and paper industry has changed over the period between 1972 and 1988 such that total loading from sewage sources decreased by almost 92% (from 15.6 to 1.3 tonnes TP/day) due to improved technologies while pulp mill loading showed little change (from 2.0 to 2.3 tonnes TP/day) despite great increases in mill production. The result was a shift from domestic sewage to pulp mill effluent as the major anthropogenic point source of TP in Finland.

With respect to TN, export from the Athabasca River increased from 298 tonnes/y near the headwaters (Athabasca River below Snaring River) to 13670 tonnes/y at Old Fort with most (87%) of the export occurring during the May-November high flow season. We estimated that pulp mills and municipalities contributed 7 and 2% of the TN load, respectively, at Old Fort during low flows compared to 2 and 0.5%, respectively, during high flows. These values are similar to the Alberta Environmental Protection (1995a) calculations of 4 and 3% TN contributions for pulp mills and municipalities during winter and 3 and 2%, respectively, during summer. For the Smoky River near Watino, 7 and 3% of the TN load is attributable to pulp mills and municipalities, respectively, during low flows compared to 2 and 0.9%, respectively, during high flows. This compares favourably with the 6% (4% from pulp mill and 2% from municipal sources) and 3% (2% from pulp mill and 1% from municipal sources) during winter and summer, respectively, reported by Alberta Environmental Protection (1995a) for the Wapiti-Smoky basin. Less information is available on pulp mill contributions to TN export for other watersheds (Table 3.2). Enell and Haglind (1994) noted that 4% of the TN load to the Gulf of Bothnia was from the pulp and paper industry with 7% from domestic sewage and 2% from other industries. Wartiovaara and Heinonen (1991) reported that between 1972 and 1988, TN loading in Finland decreased by 44% (from 72 to 40 tonnes/d) for domestic waste and remained relatively constant for pulp and paper effluents (from 15 to 13 tonnes/d) despite large increases in mill production.

While pulp and paper mills contribute 4% of the annual TP load in the Athabasca River at Old Fort and 3% of the annual TP load in the Smoky River near Watino, their nutrient loading still produces biological consequences. Thus, Scrimgeour and Chambers (1996) observed higher biomasses of benthic algae downstream of Hinton, Whitecourt and Grande Prairie compared to upstream samples in fall 1994. Scrimgeour and Chambers (1996) also reported that benthic algal growth was P-limited upstream of Hinton compared to P-saturated downstream while in the Wapiti River, algal growth was P and N-limited upstream of Grande Prairie compared to nutrient-saturated immediately downstream. Hamilton *et al.* (1985) and Anderson (1989) also observed benthic chlorophyll *a* concentrations that were up to five-fold greater downstream compared to upstream to downstream of Hinton in fall 1984. The effect of enhanced periphyton production due to effluent loading has been transferred to higher trophic levels in the food web with benthic invertebrate communities downstream of all pulp mill discharges showing increased densities. Thus, benthic invertebrate densities are greater downstream of Hinton (Anderson 1989) and Grande Prairie (Noton *et al.* 1989) compared to upstream sites. In addition, Gibbons *et al.* (1996) reported greater individual biomasses of spoonhead sculpin (*Cottus ricei*) upstream versus downstream of Hinton. These enrichment responses are particularly evident during fall when low river flow reduces effluent dilution and when water temperature and clarity are conducive for benthic production. The observed nutrient impacts on riverine biota despite the low nutrient contribution from point sources on an annual basis, are due in part to the fact that pulp mills and certain sewage discharges (e.g., Grande Prairie) are substantial contributors of nutrients during low flows. In addition, the bioavailable forms of N and P (which are responsible for increased aquatic plant growth) are proportionately more abundant in pulp mill and municipal effluents than in natural inflows. Thus, ratios of bioavailable P (determined from algal bioassays) to TP are generally high for pulp mill (e.g., approximately 80% for an activated sludge treated kraft mill in Finland (Priha 1994)) and municipal (70-100% (Sonzogni *et al.* 1982)) effluents compared to estimates for natural waters (e.g., 31% for lakes and rivers with < 30μg/L TP and 40% for rivers with TP > 30 μg/L (Bradford and Peters 1987); < 50% in rivers and run-off waters (Sonzogni *et al.* 1982)). This means that our calculations based on total N and P loading would underestimate the contribution of pulp mills and municipalities to the rivers' bioavailable nutrient loads. Indeed, results from studies conducted by Culp and Podemski (1996) in artificial streams showed that river water containing only 1% effluent from Weldwood of Canada Ltd. stimulated production of the diatom community of the upper Athabasca River in winter. Moreover, nutrient inputs from point sources do not necessarily show up immediately at downstream sites and at concentrations that would be predicted on the basis of effluent loads and instream dilution. Nutrients may be stored (in biological material or bottom sediments) and released in a different season or year from when they were released to the river. Thus, our calculations of the contribution by pulp mills and municipal effluents to TP and TN loads in the Athabasca, Wapiti and Smoky rivers undoubtedly underestimate the role of these sources in adding bioavailable nutrients to the rivers.

4.0 NUTRIENT MASS BALANCES FOR THE ATHABASCA AND WAPITI-SMOKY RIVERS

4.1 INTRODUCTION

Sentar Consultants Inc. (1994) undertook initial calculations of TP loads to the Athabasca River based on the premises that the basin was 45% forested and 55% mixed agriculture and forest, and that TP was exported from forested and agricultural/forested lands at rates of 10 and 20 kg/km^2/y, respectively. However, since the initial calculations were undertaken, several questions arose regarding the estimation of non-point source loading to the Athabasca River:

1. Given current GIS capabilities, can more accurate estimates be obtained of the area within each sub-basin of the Athabasca River devoted to different land uses (i.e., forested, agricultural and pasture land)?

2. Can the TP export coefficients that were used in the original calculations be applied to basins that are considerably smaller or larger than the basin for which they are derived? In other words, is there a scaling factor that must be applied when using export coefficients?

3. The P export calculations to date have been based on TP and not bioavailable forms of P, yet the proportion of bioavailable phosphorus in the TP load from pulp mills and sewage treatment plants is much greater than the proportion in natural TP loads. What is the yield of bioavailable N and P from non-point sources?

In this chapter, we will address these questions to determine a more accurate estimate of the total load of nutrients in the Athabasca and Wapiti-Smoky rivers and the relative contribution of anthropogenic sources. We will compare two approaches for estimating nutrient loads from the Athabasca and Wapiti-Smoky rivers:

1. summing point-source (i.e., industrial and municipal data from Tables 2.1, 2.2 and 2.3) and non-point (calculated by multiplying the area within the drainage basin for each landuse by the nutrient export coefficient for the particular landuse) loads for the entire river length, and

2. calculating total load from concentration and discharge data measured at long-term sites on the Athabasca River at Athabasca and Smoky River at Watino.

4.2 METHODS

4.2.1 Estimating Non-Point Nutrient Loading

Non-point TP, SRP and TN loads were calculated for the Athabasca River at its mouth, the Wapiti River at the confluence with the Smoky River and the Smoky River at the confluence with the Peace River. Non-point nutrient loadings were estimated by multiplying the area within the drainage basin for each landuse by the N or P export coefficient appropriate for the particular landuse (Rast and Lee 1983, Clesceri *et al.* 1986). The use of export coefficients for estimating nutrient loads is based on the knowledge that, over a year, specific types of landuse (e.g., cropland, pasture or forest) in a given climatological and geologic regime will yield or export characteristic quantities of nutrients (expressed on an areal basis) to a downstream waterbody. This nutrient export is primarily associated with overland runoff from precipitation or snow-melt. While the most accurate measures of non-point nutrient loading are obtained from direct and frequent measurement of nutrient concentrations and water volume, Rast and Lee (1983) noted that loadings estimated from export coefficients for 38 U.S. waterbodies were within a factor of two of measured loads for 35 of 38 TP estimates and 32 of 38 TN estimates.

4.2.1.1 Land use within the Athabasca, Wapiti and Smoky basins

Patterns of land use (i.e., vegetation cover) were determined for every census subdivision within each river basin. Land-use information was obtained from 1991 satellite imagery from the Advanced Very High Resolution Radiometer (AVHRR) sensor operating on board the United States National Oceanic and Atmospheric Administration (NOAA) satellites and then classified using image analysis software with a resolution of approximately 1 km^2/pixel. Vegetation cover classes within the Athabasca, Wapiti and Smoky basins are (National Atlas of Canada 1993):

1. forested land (land where forest occupies more than 50% of the area)
    - (a) coniferous forest - continuous forest in which 76-100% of the canopy is composed of coniferous trees
    - (b) broadleaf forest - continuous forest in which 76-100% of the canopy is composed of broadleaf trees
    - (c) mixed forest - continuous forest in which 26-75% of the canopy is composed of coniferous or broadleaf trees

2. sparsely vegetated or barren land (plant cover is generally sparse, less than 25% cover, and not discernible from satellite imagery)

3. agricultural land
    - (a) cropland - cultivated land with crops, fallow, feedlots, orchards, vineyards, nurseries, shelter-belts or hedgerows

(b) rangeland and pasture - land supporting native vegetation (shrubs, grasses or other herbaceous cover) with less than 10% tree cover. This includes improved land dedicated to the production of forage, and upland and lowland meadows.

4. perennial snow and ice

5. open water.

For the purposes of this report, all three forest classes were pooled; barren land and areas of perennial snow and ice cover were also pooled.

The Athabasca River drains 160,550 km^2. Forested land is the major land type, comprising 89% of the entire area, with pasture (3%) and cropland (3%) as the next most common landuses (Table 4.1). There is one large lake in the Athabasca basin, Lesser Slave Lake, with a surface area of 1160 km^2 and a drainage basin of 12400 km^2 (Mitchell and Prepas 1990). Nutrient retention in Lesser Slave Lake could not be calculated directly due to limited chemical and hydrologic data. To account for storage in the lake, a retention coefficient (R) for TP of 0.82 was estimated following the approach given in Larsen and Mercier (1976) where q_s was 1.197 and p_w was 0.105 (from values of 1550x10^6 m^3, 0.472 m, 0.611 m and 11.4 m for mean annual inflow, mean annual precipitation, mean annual evaporation and mean depth, respectively; Mitchell and Prepas 1990). Empirical models are not available for calculating SRP or TN retention coefficients. We have assumed SRP retention to be 15% greater (i.e., R = 0.94) than TP retention which is based on the findings of Trew *et al.* (1987) for Baptiste Lake, Alberta where retention coefficients (1976-1978) averaged 0.67 and 0.78 for TP and SRP, respectively. Higher SRP:TP retention ratios have been observed in other Alberta lakes, such as TP and SRP retentions of 0.65 and 0.98, respectively, for Pine Lake from February to October 1992 (D. Trew, Alberta Environmental Protection, pers. comm.). For TN, we have assumed an R of 0.43. Jensen *et al.* (1990) showed that for 69 shallow Danish lakes (0.1-41 km^2, 0.6-16 m mean depth, 127x10^6 m^3 mean annual inflow) varying widely in TN loading (142±35 g N/m^2/y) and in-lake TN concentrations (0.5-9 mg/L), 43% of the incoming TN was lost from or retained in the lake. This value compares favourably with North American lakes such as Silver Lake, Washington (R=0.50; Bhagat *et al.* 1975), Rawson Lake, Ontario (R=0.60 for 1970-73; Schindler *et al.* 1976), H. A. Andrews experimental forest, Oregon (R=0.52; Fredriksen 1972) and Baptiste Lake, Alberta (R=0.60 for 1978; Trew *et al.* 1987). However, for Pine Lake, Alberta the TN load from the lake (4256 kg) was greater than the incoming load (4178 kg) whereas in Lake Wabamun, Alberta most of the incoming TN was retained in the lake (R=0.12) (D. Trew, Alberta Environmental Protection, pers. comm.). The subdivisions 07BF, 07BG, 07BH and 07BJ drain all or in part into Lesser Slave Lake and total 14128 km^2. The landuse in these subdivisions was summed to give one large subdivision for each landuse pattern (07BF-J) and the proportion of the export (kg/y) that drained to Lesser Slave Lake (i.e., 12400/14128 x 100 = 87.8%) was multiplied by (1-R) to give the fraction transferred downstream.

The Wapiti and Smoky rivers drain 14468 and 50352 km^2, respectively. In the Wapiti and Smoky river basins, the land is 75 and 80% forested and 22 and 17% cropland, respectively (Table 4.2).

Table 4.1 Landuse within the Athabasca River drainage basin (km^2). Subdivisions illustrated in Figure 4.1. Landuse classifications defined in Section 4.2.1.1.

Subdivision	Coniferous	Deciduous	Mixed Forest	Cropland	Pasture	Water	Barren + Ice	Total Area
07AA	3297	203	1048	0	0	96	2782	7426
07AB	796	27	181	0	0	0	649	1653
07AC	5129	75	471	0	0	5	248	5928
07AD	964	269	921	0	0	125	0	2279
07AE	1976	224	650	0	0	101	0	2951
07AF	3086	32	1660	0	0	0	118	4896
07AG	1504	1459	1755	0	8	0	0	4726
07AH	3145	413	953	144	176	80	0	4911
07BA	1919	282	1474	0	119	0	0	3794
07BB	290	797	827	11	3929	133	0	5987
07BC	578	91	477	2323	272	3	0	3744
07BD	1606	322	631	173	64	146	0	2942
07BE	344	646	1253	594	32	112	0	2981
07BF	1430	3664	1534	450	0	80	0	7158
07BG	455	463	407	0	0	684	0	2009
07BH	458	671	256	0	0	200	0	1585
07BJ	1355	1257	418	0	0	346	0	3376
07BK	3912	1481	1188	0	0	64	0	6645
07CA	2262	1489	3340	709	48	381	0	8229
07CB	6372	841	2583	293	37	437	0	10563
07CC	3371	735	1699	0	0	154	0	5959
07CD	13370	705	3073	0	0	346	3	17497
07CE	7725	2093	2965	0	0	298	42	13123
07DA	3938	2016	3331	0	0	277	0	9562
07DB	1691	1174	2817	0	0	0	0	5682
07DC	3443	152	2647	0	0	3	56	6301
07DD	6260	370	1800	0	0	213	0	8643
Total	80676	21951	40359	4697	4685	4284	3898	160550
%	50	14	25	3	3	3	2	100

Table 4.2 Landuse within the Wapiti-Smoky river drainage basin (km^2). Subdivisions illustrated in Figure 4.1. Landuse classifications defined in Section 4.2.1.1.

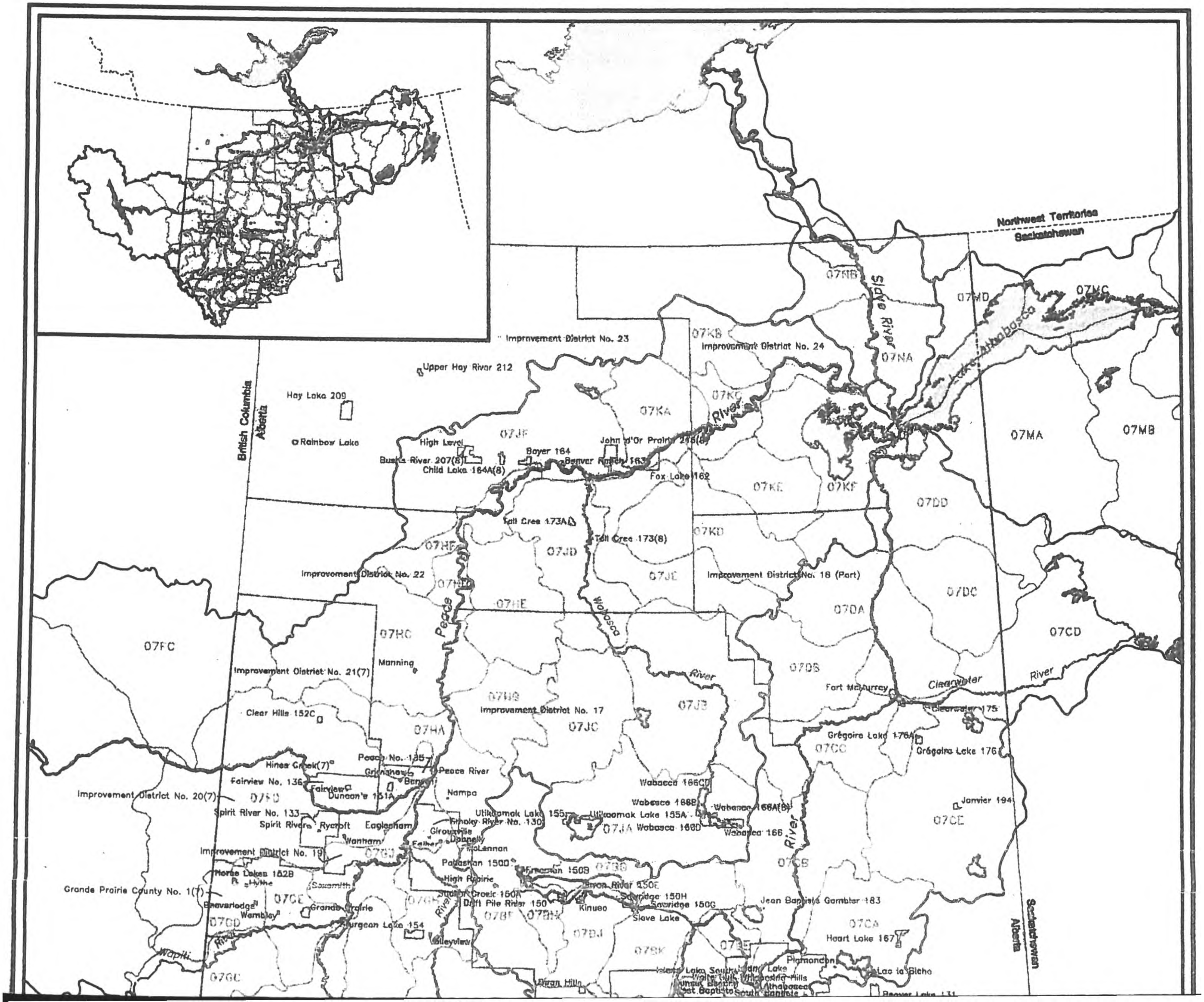
(a) Wapiti

Subdivision	Coniferous	Deciduous	Mixed Forest	Cropland	Pasture	Water	Barren + Ice	Total Area
07GC	4449	411	1825	72	0	0	359	7116
07GD	948	541	687	1065	0	5	0	3246
07GE	122	871	1025	2040	0	48	0	4106
Total	5519	1823	3537	3177	0	53	359	14468
%	38	13	24	22	0	0.5	2.5	100

(b) Wapiti-Smoky

Subdivision	Coniferous	Deciduous	Mixed Forest	Cropland	Pasture	Water	Barren + Ice	Total Area
Wapiti	5519	1823	3537	3177	0	53	359	14468
07GA	2969	194	1129	0	0	0	1203	5495
07GB	4181	505	2463	0	0	0	93	7242
07GF	1941	1936	1419	226	0	0	0	5522
07GG	4468	2049	1241	8	0	5	0	7771
07GH	0	2538	474	1763	0	107	0	4882
07GJ	107	919	706	3187	0	53	0	4972
Total	19185	9964	10969	8361	0	218	1655	50352
%	38	20	22	17	0	0.4	3	100

Figure 4.1 Athabasca and Wapiti-Smoky drainage basins showing census subdivisions.



The Digital Boundary Files of Statistics Canada comprise a library of geographic boundaries in digital form for most levels of geography (from the enumeration area up to the province and territory). With the appropriate software, Digital Boundary Files provide the framework for computer analysis and mapping. These files can also be used to create new geographic areas by aggregating standard geographic areas, and for other data manipulations available with the user's software.

Since these digital boundaries reflect the actual boundaries required to enumerate all the households in Canada, boundaries running through water bodies (such as lakes and oceans) may appear as straight lines, rather than following the shoreline. Thus, the digital boundary files may not be suitable for mapping applications where realistic shoreline is important, or for analysis requiring the computation of real land area.

Census Subdivision (CSD) refers to the general term applying to municipalities (as determined by provincial legislation) or their equivalent, e.g., Indian reserves, Indian settlements and unorganized territories.

The information shown is the CSD (Census subdivisions) digital boundary file of Statistics Canada
Ottawa: Statistics Canada, December 3, 1993

Census Subdivisions (CSDs)

Digital Boundary File

Canada Alberta Northwest Territories

Northern River Basins Study

Scale (Kilometres)

0 50 100 150 200 250

Map (PAT_C) prepared by G.W. Babish (07/18/94)

Environmental Conservation Directorate / Socio-Economic Branch / Regina

4.2.1.2 Export coefficients

Nutrient export coefficients vary considerably not only with landuse but also with locale (i.e., climate and geology) (Table 4.3). To assist in selecting appropriate nutrient export coefficients for the Athabasca and Wapiti-Smoky river systems, export coefficients measured in watersheds throughout North America were reviewed (Appendices D, E and F), with emphasis on data collected in north-central Alberta. We then selected the most appropriate nutrient export coefficients for each landuse.

4.2.1.3 TP export coefficients

TP export coefficients for 277 forested watersheds in North America averaged 10.4 ±0.7 kg TP/km^2/y (mean±S.E.; $n = 318$, some watersheds had more than one measurement) (Table 4.4). High TP exports (e.g., 20 kg/km^2/y) were usually associated with forests receiving higher precipitation levels and/or characterized as deciduous. Low TP exports (e.g., 5 kg/km^2/y) were associated with arid forested land and/or forested land dominated by conifers. Of the 277 forested watersheds, 102 were within Canada and had a mean export coefficient of 9.7±1.1 kg TP/km^2/y and of these watersheds, 12 were in northern and central Alberta (seven within the Athabasca drainage basin) and had a mean export coefficient of 12.1±2.3 kg TP/km^2/y. We chose 10 kg TP/km^2/y as a reasonable estimate of TP export from forested lands in the Athabasca and Wapiti-Smoky river basins (Table 4.5).

TP export coefficients for 198 watersheds draining primarily cropland averaged 33.0±2.3 kg TP/km^2/y (Table 4.4). Of these, 18 were within Canada and had a mean export coefficient of 34.9±5.8 kg TP/km^2/y and of these, 11 were in northern and central Alberta (five in the Athabasca drainage basin) and had a mean export coefficient of 23.1±3.2 kg TP/km^2/y. The higher values when all the North American or Canadian data were considered likely reflect more intensive agricultural practices in parts of the continent or country. For example, soil erosion and, consequently, TP loss in run-off is greater for row crops such as corn and tobacco than non-row crops such as barley, which are typical of central and northern Alberta. We chose 25 kg TP/km^2/y as a reasonable estimate of TP export from cropland in the Athabasca and Wapiti-Smoky river basins (Table 4.5).

TP export coefficients for 63 watersheds draining primarily pasture land averaged 45.6±9.3 kg TP/km^2/y (Table 4.4). Of these, 13 were within Canada and had a mean export coefficient of 43.3±7.6 kg TP/km^2/y. The one study (of 10 small drainage basins) from northern or central Alberta (Majeau Creek in the Athabasca drainage basin) reported TP export coefficients ranging from 20 to 142 kg/km^2/y with an average of 68.5±12.2 kg/km^2/y (Mitchell and Hamilton 1982). Reckhow *et al.* (1980) reviewed 14 studies of TP export coefficients for grazed and pastured watersheds and found values ranging from 14 to 490 kg TP/km^2/y (mean 150 kg/km^2/y). Many of these export coefficients were derived from areas in the south and central United States with high rainfall, year-round grazing or intensive fertilizer application and may not be applicable to Alberta (Mitchell and Hamilton 1982). In contrast, Omnerick (1977) reviewed TP export coefficients for grazed or pasture land largely located in arid regions of western and south-western U.S.A. These pastures were classified as rangelands and most were not

Table 4.3 TP export coefficients (kg/km^2/y) from selected studies showing the range in values for different landuses and geographic areas.

Landuse	Two Athabasca River tributaries (Munn and Prepas 1986)	Eastern United States (Omnerick 1976)	Western United States (Omnerick 1977)	United States national average (Rast and Lee 1983)	Central Ontario (Dillon *et al.* 1991)	Wisconsin (Clesceri *et al.* 1986)	Southern Ontario (Dillon and Kirchner 1975)
forest	7.5 -13	8.3-17.4	9.1-16.6	5 -10	2-34	11.2	4.8 - 10.7
agriculture	-	22.7-30.8	21.2-26.6	50	-	26.2	-

Table 4.4 Summary statistics (mean±standard error, median, interquartile range and number of observations) for total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN) and dissolved inorganic nitrogen (DIN) export coefficients for forested, agricultural and pasture land in North America. (Raw data in Appendices D, E and F.)

Export Coefficients (kg/km^2/y)	Forested				Cropland				Pasture			
	Mean±SE	Median	Range	N	Mean±SE	Median	Range	N	Mean±SE	Median	Range	N
TP												
all data	10.4±0.7	7.9	4.7-12.0	318	33.0±2.3	24.1	12.28-39.0	250	45.6±9.3	13.1	4.6-32.3	94
Canada	9.7±1.1	7.1	4.5-10.8	124	34.9±5.8	26	10-40	33	43.3±7.6	24.5	20.6-63	22
north-central Alberta	12.1±2.3	12	7.2-15	27	23.1±3.2	21	9-36	26	68.5±12.2	68	38-80.5	10
SRP												
all data	5.3±0.3	4	2.5-5.5	235	11.8±0.9	8.9	4.4-15.6	181	10.0±2.4	3.5	0.8-10	60
Canada	4.0±0.5	3.2	2-5	57	20.1±2.4	21	11-26	21	23.5±5.9	11.8	8.9-27.7	20
north-central Alberta	4.8±1.2	3	3-8	17	16.9±2.6	17	9.5-22	14	40.2±10.7	32	20.5-40.5	9
TN												
all data	311±20	236	102-426	208	694±43	479	209-1196	192	350±49	229	82-400	90
Canada	162±36	102	67-165	39	519±152	177	64-256	32	351±34	351	245-402	20
north-central Alberta	132±26	91	64-176	25	142±21	109	48-216	26	320±73	228	156-406	9
DIN												
all data	71.7±5.8	37.2	16.7-83	155	573±42	363	121-1032	166	47±15	18.3	8.8-57.8	40
Canada	n/a	n/a			1809±286	1846	1569-2262	6	n/a	n/a		
north-central Alberta	n/a	n/a			n/a	n/a			n/a	n/a		

Table 4.5 Suggested export coefficients (kg/km^2/y) for total phosphorus (TP), soluble reactive phosphorus (SRP) and total nitrogen (TN) for specific landuses in the Athabasca and Wapiti-Smoky river basins.

Land use	TP	SRP	TN
Forest	10	5	135
Cropland	25	15	150
Pasture land	50	25	300
Atmospheric loading to waterbodies, barren land and icefields	20	10	400

fertilized and were marginal agricultural land. TP export coefficients for these areas ranged from 0.1 to 51.3 kg/km^2/y and averaged 7 kg/km^2/y. We chose 50 kg TP/km^2/y as a reasonable estimate of TP export from pasture land in the Athabasca and Wapiti-Smoky river basins (Table 4.5). Mitchell and Hamilton (1982) likewise recommended use of a TP export coefficient of 50 kg/km^2/y for watersheds largely used for livestock production.

Atmospheric loading of TP from precipitation and dry fallout was set at 20 kg/km^2/y. Shaw *et al.* (1989) determined that atmospheric deposition of TP was 20.3 kg/km^2/y for Narrow Lake in central Alberta while values for other lakes on sedimentary bedrock in central Alberta were 20.6±2.2 kg/km^2/y (Shaw *et al.* 1989 after Mitchell 1985, Trew *et al.* 1987, Pollution Control Division, Alberta Environment, unpublished data). As export coefficients are not available for barren land and icefields, coefficients for atmospheric loading were applied to these land types on the assumption that runoff from these nutrient-poor lands would be similar to precipitation.

4.2.1.4 SRP export coefficients

Studies of the relationship between TP and SRP export coefficients have generally found that export coefficients for SRP are usually 40 to 50% of that for TP and that this ratio is independent of landuse. Thus, Clesceri *et al.* (1986) found that for watersheds in Michigan, export coefficients for SRP were approximately 50% of those for TP. Omnerick (1976) reported that for 473 watersheds in the U.S.A. without point-source loadings, SRP export was typically 40-43% of TP export regardless of landuse. In a later study, Omnerick (1977) likewise noted that for 928 watersheds in the U.S.A. without point-source loadings, SRP was approximately 40 to 50% of the TP load regardless of landuse. The 0.4 to 0.5 ratio of SRP to TP export for watersheds with only non-point loadings does not necessarily apply to watersheds receiving point sources of nutrient loading. Measurements of SRP and TP loads in seven watersheds in South Africa showed that the ratio of SRP to TP export was 0.2 to 0.3 in watersheds containing mainly non-point loadings as compared to 0.6 to 0.9 in watersheds dominated by point-source loading (Grobler and Silberbauer 1985). The higher proportion of SRP in the TP load of watersheds receiving point-source loading is likely due to the higher percentage of available P in sewage effluent (70 to 100 % of TP in municipal effluent is bioavailable; DePinto *et al.* 1980, Sonzogni *et al.* 1982).

SRP export coefficients for 178 forested watersheds in North America averaged 5.3±0.3 kg/km^2/y (Table 4.4). Of these, 11 were within Canada and had a mean export coefficient of 4.0±0.5 kg SRP/km^2/y and of these watersheds, seven were in northern and central Alberta (all within the Athabasca drainage basin) and had a mean export coefficient of 4.8±1.2 kg/km^2/y. We chose 5 kg TP/km^2/y as a reasonable estimate of SRP export from forested lands in the Athabasca and Wapiti-Smoky river basins (Table 4.5).

SRP export coefficients for 172 watersheds draining primarily cropland averaged 11.8±0.9 kg/km^2/y (Table 4.4). Of these, 12 were within Canada (mostly eastern Canada) and had a mean export coefficient of 20.1±2.4 kg TP/km^2/y and of the 12 watersheds, five were in northern or central Alberta (all in the Athabasca drainage basin) and had a mean export coefficient of 16.9±2.6 kg/km^2/y. As with the TP export coefficients for cropland, the higher values when all Canadian data were considered likely reflect more intensive agricultural practices in the eastern part of the country. We chose 15 kg/km^2/y as a reasonable estimate of SRP export from cropland in the Athabasca and Wapiti-Smoky river basins (Table 4.5).

SRP export coefficients for 51 watersheds draining primarily pasture land averaged 10.0±2.4 kg/km^2/y (Table 4.4). Of these, 11 were within Canada and had a mean export coefficient of 23.5±5.9 kg/km^2/y. The one study (nine small drainage basins) from northern or central Alberta (Majeau Creek in the Athabasca drainage basin) reported export coefficients for SRP ranging from 50 to 80% of those for TP (i.e., 10 to 116 with a mean of 40.2±10.7 kg SRP/km^2/y) (Mitchell and Hamilton 1982). This small watershed probably reflects typical grazing and forage production land for the region. We chose SRP export from pasture to be 50% of TP export, i.e. 25 kg/km^2/y (Table 4.5).

Atmospheric loading of SRP from precipitation and dry fallout was set at 50% of TP atmospheric loading, namely 10 kg/km^2/y. Estimates of bioavailability of atmospheric nutrients in Eastern Canada suggest that bioavailability is as much as 100% TP in rain (Peters 1977), 24% of TP in snow (Peters 1977) and 57% of TP in dry fallout (Shaw *et al.* 1989 after Gomolka 1975). As export coefficients are not available for barren land and icefields, coefficients for atmospheric loading were applied to these land types on the assumption that runoff from these nutrient-poor lands would be similar to precipitation.

4.2.1.5 TN export coefficients

TN export coefficients for 176 forested watersheds in North America averaged 311±20 kg TN/km^2/y (Table 4.4). While low TN export coefficients were usually associated with arid forested land and/or forested land dominated by conifers, the fact that N is often the most limiting nutrient for terrestrial plant growth may result in the demand for N by growing vegetation overshadowing the effect of physiographic or climatic factors on nitrogen export (Beaulac and Reckhow 1982). Of the 176 forested watersheds, 13 were within Canada and had a mean export coefficient of 162±36 kg TN/km^2/y and of these watersheds, 10 were in northern and central Alberta (five within the Athabasca drainage basin) and had a mean export coefficient of 132 ±26 kg TN/km^2/y. We chose 135 kg TN/km^2/y as a reasonable estimate of TN export from forested lands in the Athabasca and Wapiti-Smoky river basins (Table 4.5).

TN export coefficients for 177 watersheds draining primarily cropland averaged 694±43 kg TN/km^2/y (Table 4.4). Of these, 18 were in Canada and had a mean export coefficient of 519±152 kg TN/km^2/y and of these, 11 were in northern and central Alberta (five in the Athabasca drainage basin) and had a mean export coefficient of 142±21 kg TN/km^2/y. The higher values when all the North American or Canadian data were considered likely reflect more intensive agricultural practices in parts of the continent or country. For example, soil erosion and, consequently, TN loss in run-off is greater for row crops such as corn and tobacco than non-row crops such as barley, which are typical of central and northern Alberta. We chose 150 kg TN/km^2/y as a reasonable estimate of TN export from cropland in the Athabasca and Wapiti-Smoky river basins (Table 4.5).

TN export coefficients for 60 watersheds draining primarily pasture land averaged 350±49 kg TN/km^2/y (Table 4.4). Of these, 11 were within Canada and had a mean export coefficient of 351±34 kg TN/km^2/y. The one study (nine small basins) from northern or central Alberta (Majeau Creek in the Athabasca drainage basin) reported TN export coefficients ranging from 100 to 713 kg/km^2/y with an average of 320±73 kg/km^2/y (Mitchell and Hamilton 1982). Our observation that in Alberta, TN export coefficients were greater for pasture land than for forested or cropland is not consistent with findings from our North American or Canadian data sets or results of others (e.g., Beaulac and Reckhow 1982) that TN export coefficients are greatest for cropland and lower for forested and pasture land. This may be due to differences in physiography since estimates of export coefficients for forested and croplands in Alberta were largely from Lake Wabamun and Baptiste Lake basins (Mitchell 1985, Trew *et al.* 1987) whereas export coefficients for pasture land came from the Majeau Creek watershed (Mitchell and Hamilton 1982). We chose 300 kg TN/km^2/y as a reasonable estimate of TN export from pasture land in the Athabasca and Wapiti-Smoky river basins (Table 4.5).

Atmospheric loading of TN from precipitation and dry fallout was set at 400 kg/km^2/y. Shaw *et al.* (1989) determined that atmospheric deposition of TN was 424 kg/km^2/y for Narrow Lake in central Alberta while values for other lakes on sedimentary bedrock in central Alberta were 358±34 kg/km^2/y (Shaw *et al.* 1989 after Mitchell 1985; Trew *et al.* 1987; Pollution Control Division, Alberta Environment, unpublished data). As export coefficients are not available for barren land and icefields, coefficients for atmospheric loading were applied to these land types on the assumption that runoff from these nutrient-poor lands would be similar to precipitation.

4.2.1.6 Dissolved Inorganic Nitrogen (DIN) export coefficients

DIN export coefficients for 155 forested watersheds in North America averaged 72±6 kg DIN/km^2/y (Table 4.4). None of these watersheds were in Canada. DIN export coefficients for 166 watersheds draining primarily cropland averaged 573±42 kg DIN/km^2/y ($n = 166$). Of these, six were in eastern Canada and had a mean export coefficient of 1809±286 kg DIN/km^2/y. There were no data available for croplands in Alberta. DIN export coefficients for 40 watersheds draining primarily pasture land averaged 47±15 kg DIN/km^2/y ($n = 40$). None of these watersheds were located in Canada. Given the scarcity of DIN export coefficients for watersheds in Canada and, particularly, Alberta and thus the difficulty in selecting appropriate DIN coefficients for north-central Alberta, we have not attempted to estimate DIN export for the Athabasca and Wapiti-Smoky basins.

4.2.1.7 Scaling of export coefficients

Nutrient export coefficients are usually expressed on an areal basis to allow application to other watersheds that may be larger or smaller than the original study basin. Application of export coefficients to basins of considerably different size assumes that nutrient export is a linear function of drainage area.

For forested basins, Prairie and Kalff (1986) found that TP export (expressed as mass per year) was linearly related to drainage area with the slope of the log TP to log area relationship ($b = 0.99$, $n = 94$) not significantly different from unity ($P > 0.50$). Our examination of 310 paired observations for forested watersheds in North America ranging in area from 0.0001 to 245,454 km^2 also showed a linear relationship between TP export and drainage area (both expressed as logarithms) with a slope not significantly different from 1 ($b=1.04$, $t=1.92$, $P > 0.05$; Appendix G). Likewise, SRP and TN export were linearly related to drainage area (both expressed as logarithms) with a slope not significantly different from unity ($b=0.97$ and 1.04, $t=1.30$ and 0.88, $n=224$ and 205 for SRP and TN export, respectively; $P > 0.1$). These results show that export coefficients for TP, SRP and TN from forested watersheds can be applied to basins of varying size.

For croplands in North America, slopes of TP or SRP export versus drainage area relationships were significantly different from 1 ($b=0.88$ and 0.85, $t=3.28$ and 2.51, $n=250$ and 181, $P < 0.02$; Appendix G). However, the slope was not significantly different ($P > 0.2$; Appendix G) from unity when only the Canada or Alberta data were considered. Prairie and Kalff (1986) reported that for agricultural land, row crops had a slope for TP export that was significantly different from unity whereas slope was not significantly different from 1 for non-row crops. The fact that slopes were not significantly different from unity for our Canada and Alberta data is likely due to the large percentage of non-row crops in these areas (55% of cropland area is non-row crops for six Ontario watersheds for which data are available). Since we observed a slope not significantly different from unity for the Canada and Alberta data and cropland in the Athabasca and Wapiti-Smoky basins is of the non-row variety, we have assumed that TP and SRP export from cropland scale linearly with drainage area.

For TN export from cropland, the delivery of nutrients per unit area increased with increasing drainage area for both the North American and Canadian data sets ($b=1.18$ and 1.41, $t=2.49$ and 2.86, $n=192$ and 32, $P < 0.02$; Appendix G). In contrast, the slope of the log-log relationship for TN export versus drainage area for the Alberta data was not significantly different from 1 ($b=1.07$, $t=0.65$, $n=26$, $P > 0.5$). The discrepancy between the Alberta and the Canadian and North American data sets may be due to the fact that the Alberta watersheds were usually small in size (21 of the 26 observations were for basins $\leq$ 10 km^2) compared to the North American (45 of 192 observations from basins $\leq$ 10 km^2) and, to a lesser extent, the Canadian (21 of 32 observations from basins $\leq$ 10 km^2) basins. As agricultural watersheds in north-central Alberta appear smaller in size than others in North America (note that the values in Tables 4.1 and 4.2 represent a sum of all the areas of similar landuse scattered throughout a sub-basin and are not necessarily one continuous area) and TN export per unit area in Alberta croplands is not drainage area dependent, we have assumed that TN export from cropland scales linearly with drainage area.

For pasture land, slopes of the TP, SRP or TN export versus drainage area relationships were significantly different from unity ($P < 0.001$, Appendix G) for the North American and Canadian data sets, with the exception of TN for the Canadian data set. When only the Alberta data were considered (n=9 or 10), slopes of the relationships were not significantly different from unity ($P > 0.2$). Given slopes of 0.90, 0.95 and 1.08 for the TP, SRP and TN relationships, respectively, for pasture land in Alberta and the fact that pasture land represents 3% of the area of the Athabasca basin (and thus changes in loading from pastured land will have little affect on the total river load), we have assumed that TP, SRP and TN export from pasture land scales linearly with drainage area.

4.2.2 Point-Source Loads

Point-source loads of TP and TN for pulp mills in the Athabasca and Smoky river basins are presented in Table 2.2. Data on SRP were not available for any mill. For calculation of total SRP loads from mills, we assumed that the 80% of the TP load for mill effluent was bioavailable. This value was based on Priha's (1994) estimate that approximately 80% of TP was available to algae in an activated sludge treated kraft mill effluent. For this mill, TDP and SRP represented 79 and 67% of TP. Priha (1994) noted that the percentage of biologically-available P will vary with changes in the ratios of soluble and particulate P to TP. TDP:TP ratios for the northern Alberta mills were less than the 79% reported by Priha (1994) for his study mill in Finland (48, 68, 57, 44, 56, 52% for Weldwood of Canada Ltd., Alberta Newsprint Co., Millar Western Pulp Ltd., Slave Lake Pulp Corp, AlPac and Weyerhaeuser Canada Ltd., respectively). SRP values are only available for Weldwood of Canada Ltd., which has a SRP:TP ratio of 0.62 (n=5, fall 1994; Podemski and Culp, unpubl. data). This value is similar to the 0.67 SRP:TP reported by Priha (1994).

Point-source loads of TP and TN for municipalities and non-pulpmill industries in the Athabasca and Wapiti-Smoky drainage basins are presented in Tables 2.1 and 2.3. Data on SRP were not available for any municipal or non-pulpmill industrial effluent. We assumed SRP loads were 70% of TP loads, based on De Pinto *et al.* (1980) findings that approximately 70% of TP in treated municipal effluents is bioavailable.

4.2.3 Inputs from Fertilized Land

To assess whether fertilizer run-off contributes significantly to the nutrient load in the Athabasca and Wapiti rivers, data on area of land fertilized for municipal districts, counties and improvement districts were obtained from Alberta Agriculture from their 1991 census. Sixteen municipal districts, counties and improvement districts were located whole or in part in the Athabasca drainage basin; three counties and improvement districts were located in the Wapiti drainage basin (Table 4.6). Using LANDSAT data in a three-way cross-reference for district, drainage basin and cropland, we calculated the area of cropland within each district that is also included within the Athabasca or Wapiti drainage basin (Table 4.7). These values for each county were then multiplied by the percent of cropland fertilized within each county (from Table 4.6) to estimate the area of fertilized cropland within the Athabasca and Wapiti drainage basins (Table 4.7).

Agricultural lands in the Athabasca and Wapiti-Smoky drainage basins are typically fertilized with 67 kg/ha N and 34 kg/ha P (B. English, Prairie Farm Rehabilitation Agency, Peace River, pers. comm.). In a review on the loss of P from fertilized fields, Sharpley *et al.* (1993) noted that the P loss from fertilized fields was generally less than 5% of the applied P, with the actual loss determined by the rate, time and method of fertilizer application, form of fertilizer, amount and duration of rainfall or irrigation, and vegetative cover. Other studies in Minnesota (Burwell *et al.* 1975) and Louisiana (Dunigan *et al.* 1976) reported that loss of fertilizer nutrients in runoff was generally less than 1% of the total amount of the nutrient applied. Nicholaichuk and Read (1978) measured nutrient losses under extreme conditions (i.e., fertilizer was applied to soils which did not require fertilizer under normal farming practices and was not incorporated into the soil so as to maximize nutrient runoff). Under these conditions TP loss averaged 2.9% of the applied P. To estimate nutrient losses from fertilizer, we used a figure of 1% loss of the total amount of the nutrient applied.

4.3 RESULTS

4.3.1 Athabasca River

On the basis of nutrient export from each land use, we estimated that 1920 tonnes/y of TP were contributed to the Athabasca River from non-point sources (Table 4.8; calculations given in Appendix H). Point sources with continuous discharge contributed 131 tonnes/y TP for a total export of 2051 tonnes/y TP from the Athabasca River. Calculations based on measured TP concentrations and discharge gave the TP load for the Athabasca River at Old Fort as 2311±701 tonnes/y (mean±95% confidence limit; Table 4.9). Our landuse estimate of TP export of 2051 tonnes/y falls within the 95% confidence limits of measured loads for the Athabasca River at Old Fort (i.e. 2311±701 tonnes/y).

Of the total export of TP from the Athabasca River, most (94%) was from non-point sources with forested land being the largest contributor (Table 4.8). Agricultural land (fertilized cropland and unfertilized pasture land) contributed only 17% of the total TP export although this contribution is disproportionately high given that agricultural land covers only 3% of the basin. To assess whether fertilizer run-off contributes significantly to the nutrient load in the Athabasca River, we determined the area of land fertilized in the Athabasca drainage basin and typical P application rates, and then estimated P loss from fertilizer as 1% of the total amount applied. Only 63% of the cropland or 1.7% of the total

Table 4.6 **Municipal, county and improvement districts located whole or in part in the Athabasca and Wapiti drainage basins, and the fertilized cropland within each district.**

(a) Athabasca drainage basin

Municipality, County or Improvement District	Area of each district (km^2)	Cropland area within each district (km^2)	Fertilized area within each district (km^2)	% fertilized cropland within each district
Athabasca County No.12	4555	1136	699	61.5
Lac Ste. Anne County No. 28	2990	1120	463	41.3
Barrhead County No. 11	2411	1144	723	63.2
Parkland County No. 31	2687	899	523	58.2
Thornhild County No. 7	1967	917	620	67.6
Brazeau M.D. No. 77	3014	366	135	36.9
Smoky River M.D. No. 130	2799	1909	1280	67.0
Sturgeon M.D. No. 90	2200	1562	1226	78.5
Westlock M.D. No. 92	3143	1763	1285	72.9
Improvement District No. 15	7540	271	140	51.8
Improvement District No. 14	25115	616	283	46
Improvement District No. 16	34088	1294	575	44.4
Improvement District No. 17	72166	1840	866	47.0
Improvement District No. 18	92566	877	285	32.5
I.D. No. 12 (Jasper National Park)	10933	0	0	0
I.D. No. 24 (Wood Buffalo Nat. Park)	34334	0	0	0

(b) Wapiti drainage basin

Municipality, County or Improvement District	Area of each district (km^2)	Cropland area within each district (km^2)	Fertilized area within each district (km^2)	% fertilized cropland within each district
Grande Prairie County No.1	5557	2811	1843	65.6
Improvement District No. 16	34088	1294	575	44.4
Improvement District No. 20	5657	1504	702	46.7

Table 4.7 **Cropland in municipal, county and improvement districts lying within the Athabasca and Wapiti drainage basins.**

(a) Athabasca drainage basin

Municipality, County or Improvement District	Cropland area within Athabasca drainage basin (km^2)	% cropland within district that is fertilized	Fertilized cropland area within the Athabasca drainage basin (km^2)
Athabasca County No.12	1302	61.5%	801
Barrhead County No. 11	375	63.2%	237
Smoky River M.D. No. 130	138	67.0%	92
Westlock M.D. No. 92	1672	72.9%	1219
Improvement District No. 15	211	51.8%	109
Improvement District No. 17	471	47.0%	221
Improvement District No. 18	209	32.5%	68
Totals	**4378**		**2747**

(b) Wapiti drainage basin

Municipality, County or Improvement District	Cropland area within Wapiti drainage basin (km^2)	% cropland within district that is fertilized	Fertilized cropland area within the Wapiti drainage basin (km^2)
Grande Prairie County No.1	88	44.4%	39
Improvement District No. 16	2986	65.6%	1959
Improvement District No. 20	1.4	46.7%	0.7
Totals	**3075.4**		**1999**

Table 4.8 **Non-point and point source loads of TP, SRP and TN to the Athabasca, Wapiti and Smoky rivers. (Loadings from AlPac not included to allow comparison with data in Table 4.9.)**

(a) Athabasca River

Sources	TP		SRP		TN	
	Load (tonnes/y)	% of Total Load	Load (tonnes/y)	% of Total Load	Load (tonnes/y)	% of Total Load
Non-Point						
Forested land	1410	68.7	712	65.9	18468	76.6
Cropland	116	5.7	70	6.5	671	2.8
Pasture land	234	11.4	117	10.8	1406	5.8
Atmospheric	160	7.8	81	7.5	3011	12.5
Total	1920	93.6	980	90.7	23556	97.6
Point[1]						
Pulp mills	95	4.7	76	7.0	312	1.3
Other	36	1.8	25	2.3	257	1.1
Total	131	6.4	101	9.3	569	2.4
Total Load	**2051**	**100**	**1081**	**100**	**24125**	**100**

(b) Wapiti River

Non-Point						
Forested land	109	45.0	54	38.3	1469	61.9
Cropland	79	32.6	48	34.0	477	20.1
Pasture land	0	0	0	0	0	0
Atmospheric	8	3.3	4	2.8	165	7.0
Total	196	81.0	106	75.2	2111	89.0
Point						
Pulp mill	26	10.7	21	14.9	171	7.2
Other	20	8.3	14	9.9	91	3.8
Total	46	19.0	35	24.8	262	11.0
Total load	**242**	**100**	**141**	**100**	**2373**	**100**

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[1] includes all municipalities and pulp mills (except Alberta Pacific Forest Industries Inc.) in Tables 2.1 and 2.2 as well as Athabasca River Suncor Oil Sands Group (Table 2.3). Loadings from Alberta Pacific Forest Industries Inc. not included to allow comparison with measured loads available only up to 1993.

(c) Smoky River

Non-Point						
Forested land	401	57.7	201	52.6	5416	70.4
Cropland	209	30.1	125	32.7	1254	16.3
Pasture land	0	0	0	0	0	0
Atmospheric	37	5.3	19	5.0	749	9.7
Total	647	93.1	345	90.3	7419	96.4
Point Sources						
Pulp mill	26	3.7	21	5.5	171	2.2
Other	22	3.3	16	4.2	103	1.3
Total	48	7.0	37	9.7	274	3.6
Total load	**695**	**100**	**382**	**100**	**7693**	**100**

Table 4.9 TP and TN loads (mean±S.E. (*n*)) for the Athabasca River at Old Fort, the Wapiti River at the mouth, and the Smoky River at Watino. Load calculations given in Section 3.2.1 and presented in Figure 3.5.

Site	TP (tonnes/y)	TN (tonnes/y)	Years of Data
Athabasca River at Old Fort	2311±400 (56)	13670±1969 (39)	1988-1992
Smoky River at Watino	2442±421 (150)	6421±1179 (53)	TP: 1980-1992 TN: 1987-1992
Wapiti River at mouth	204±109 (24)	1335±428 (23)	1991-1993

area of the Athabasca drainage basin is fertilized (Table 4.7). Using a figure of 1% loss of applied P, a fertilizer application rate 34 kg/ha/y P, and 2747 km^2 of fertilized land in the Athabasca drainage basin, we estimated that runoff from fertilizer application in the Athabasca River basin accounts for 93 tonnes/y P. This value is comparable to our estimates based on landuse and export coefficients of 116 tonnes/y TP exported from cropland in the Athabasca River basin.

On the basis of nutrient export from each land use, we estimated TN export from the Athabasca River to be 24125 tonnes/y, with 23556 tonnes/y from non-point sources and 569 tonnes/y from point sources (Table 4.8; calculations given in Appendix H). Calculations based on measured TN concentrations and discharge gave the TN load for the Athabasca River at Old Fort as 13670±3452 tonnes/y (mean±95% confidence limit; Table 4.9). Of the total export of TN from the Athabasca River, most (97%) was from non-point sources with forested land being the largest contributor (Table 4.8). Agricultural land (fertilized cropland and unfertilized pasture land) contributed 8.7% of the total TN export.

Estimates of SRP export from the Athabasca River based on land use and export coefficients gave 1081 tonnes/y, with 980 tonnes/y from non-point sources and 101 tonnes/y from point sources (Table 4.8; calculations given in Appendix H). Data are not available of measured SRP loads for comparison with the values estimated from export coefficients. Of the total SRP export from the Athabasca River, most (91%) was from non-point sources with forested land being the largest contributor (Table 4.8). Agricultural land (fertilized cropland and unfertilized pasture land) contributed 17% of the total SRP export.

4.3.2. Wapiti-Smoky Rivers

On the basis of nutrient export from each land use, we estimated that 196, 106 and 2111 tonnes/y of TP, SRP and TN, respectively, were contributed to the Wapiti River from non-point sources (Table 4.8; calculations given in Appendix I). Point sources with continuous discharge contributed 46, 35 and 262 tonnes/y TP, SRP and TN, respectively, for total exports of 242, 141 and 2373 tonnes/y TP, SRP and TN, respectively, from the Wapiti River. Based on measured values of nutrient concentrations and discharge, we calculated export for the Wapiti River at the mouth to be 204±174 tonnes/y TP and 1335±685 tonnes/y TN (mean±95% confidence limits; Table 4.9). Our estimate of TP export from land use falls within the 95% confidence limits of observed export, however our estimate of TN export is greater than the measured export. Of the annual export of TP from the Wapiti River, most (81%) was from non-point sources with forested land being the largest contributor (Table 4.8). Agricultural land (fertilized cropland) contributed 36% of the annual TP export. To assess whether fertilizer run-off contributes significantly to the nutrient load in the Wapiti River, we determined the area of land fertilized in the Wapiti drainage basin and typical P application rates, and then estimated P loss from fertilizer as 1% of the total amount applied. Only 46% of the cropland or 14% of the total area of the Wapiti drainage basin is fertilized (Table 4.7). Using a figure of 1% loss of applied P, a fertilizer application rate of 34 kg/ha/y P, and 1999 km^2 of fertilized land in the Wapiti drainage basin, we estimated that runoff from fertilizer application in the Wapiti River basin accounts for 70 tonnes/y P.

This value is comparable to our estimates based on landuse and export coefficients of 79 tonnes/y TP exported from cropland in the Wapiti River basin.

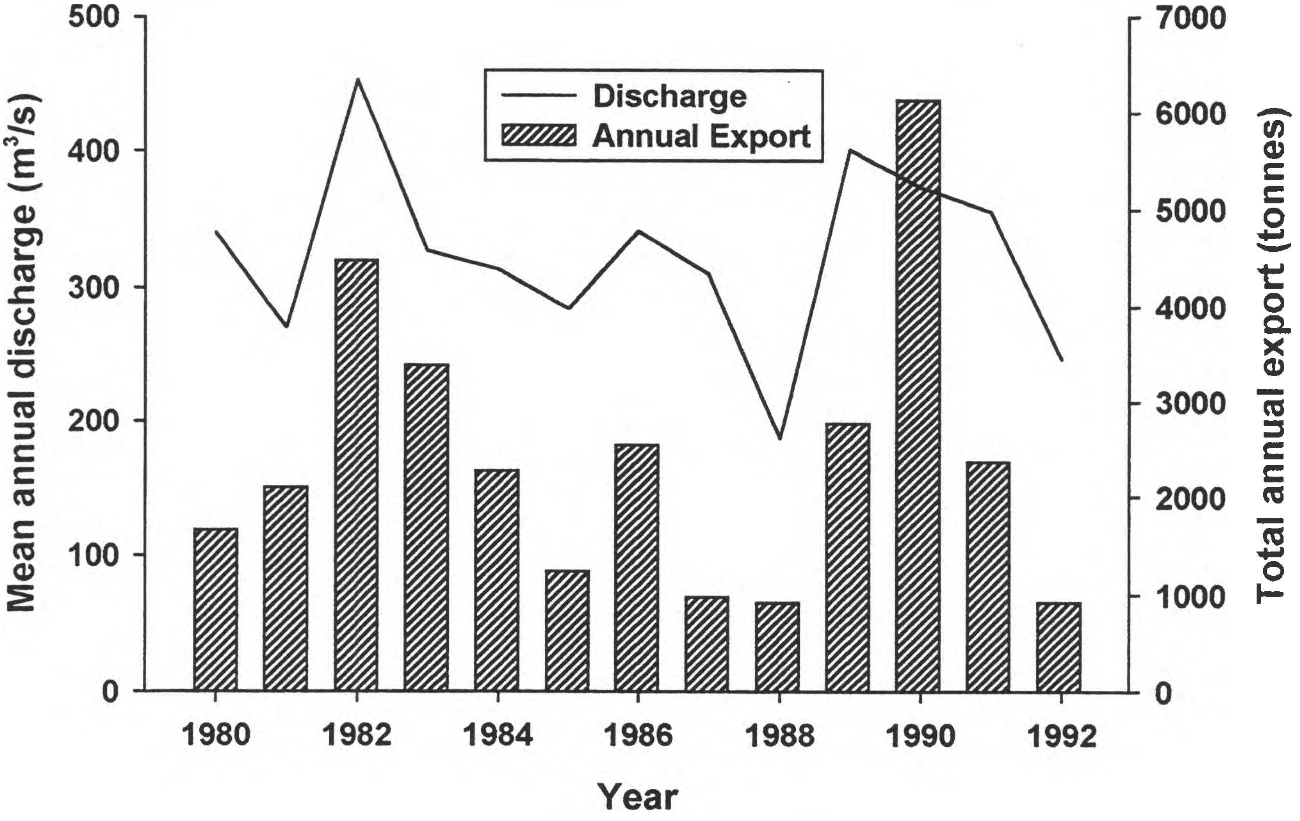
For the Smoky River, we estimated that 647, 345 and 7419 tonnes/y of TP, SRP and TN, respectively, were contributed from non-point sources (Table 4.8; calculations given in Appendix J). Point sources with continuous discharge contributed 48, 37 and 274 tonnes/y TP, SRP and TN, respectively, for total exports of 695, 382 and 7693 tonnes/y TP, SRP and TN, respectively, from the Smoky River. Of the total export of TP, SRP and TN from the Smoky River, most (> 90%) was from non-point sources with forested land being the largest contributor (Table 4.8). Agricultural land (fertilized cropland) contributed 16 to 33% of the annual TP, SRP and TN export. Calculations based on measured concentrations and discharge gave nutrient loads for the Smoky River at Watino as 2442±793 tonnes/y TP (mean±95% confidence limit) and 6421±2067 tonnes/y TN (mean±95% confidence limit) (Table 4.9). Our landuse estimate of TP export of 695 tonnes/y is considerably less than the measured export of 2442 tonnes/y.

4.4 DISCUSSION

On the basis of nutrient export from each land use, we estimated that 1920, 196 and 647 tonnes/y of TP were contributed to the Athabasca, Wapiti and Smoky Rivers from non-point sources (Table 4.8). Point sources with continuous discharge contributed 131, 46 and 48 tonnes/y for a total export of 2051, 242 and 695 tonnes/y TP from the Athabasca, Wapiti and Smoky rivers, respectively. Our estimate of 2051 tonnes/y TP export for the Athabasca River is similar to the value of 2104 tonnes/y estimated by Sentar Consultants Ltd. (1994) on the basis of landuse patterns and export coefficients. It is also similar to calculations based on measured TP concentrations and discharge, namely 2311±701 tonnes/y (mean±95% confidence limit; Table 4.9) for 1988-1992 and Noton's (1990) value of 3504 tonnes/y based on 1977-1988 data. Likewise, the measured value of TP export for the Wapiti River, 204±174 tonnes/y (mean±95% confidence limit; Table 4.9), is similar to our predicted value, 242 tonnes/y TP. This indicates that use of export coefficients and land use patterns provide a reasonable estimate of TP export for the Athabasca and Wapiti rivers. However, our predicted TP load for the Smoky River was almost four-fold less than the observed load (695 compared to 2442 tonnes/y). This is surprising given that export coefficients gave a good estimate of TP loading for the Wapiti River, which represents 29% of the area of the Smoky River watershed. Our observed load for the Smoky River was based on a larger data set than was available for most other sites on the Athabasca and Wapiti rivers (1980-1992 and 150 data points; Table 4.9) and there was considerable inter-year variability in TP export that appeared related to river discharge (Figure 4.2). The higher TP load based on field measurement compared to landuse predictions may relate to bed-load transport of P during high flow years.

Based on N export coefficients and landuse patterns, we estimated TN export from the Athabasca, Wapiti and Smoky rivers to be 24125, 2373 and 7693 tonnes/y, respectively. Our value of 24125 tonnes/y TN export from the Athabasca River is greater than our calculated value of 13670±3452 (mean±95% confidence limit for 1988-1992) for the Athabasca River at Old Fort but similar to the 22995 tonnes/y calculated by Noton (1990) for 1977-1988. The lower value we calculated for 1988-

Figure 4.2 Mean annual discharge and TP export for the Smoky River at Watino.



1992 may relate to lower discharges during this period (650 m^3/s grand mean of annual discharge for 1988-1992) than the mean annual value of 783 m^3/s for Noton's (1990) 1977-1988 calculations. For the Smoky River, the estimated TN load fell with the 95% confidence limits of the observed load (6421±2067 tonnes/y) while estimated TN loads were above the 95% confidence limits of the observed mean values (2373 tonnes/y estimated compared to 1335±685 tonnes/y) for the Wapiti River at the mouth.

Based on SRP export coefficients and landuse patterns, we estimated SRP from the Athabasca, Wapiti and Smoky rivers to be 1081, 141 and 382 tonnes/y, respectively. SRP data are not available to determine SRP loads for comparison with the estimated values. However, Noton (1990) calculated that TDP loads for the Athabasca River at Old Fort were 190 tonnes/y (1987-1988) which would indicate that our estimated SRP load of 1081 tonnes/y is an over-estimate. Given that reaches of the Athabasca River are P limited, much of the SRP load to the river may be taken up by primary producers.

Of the total export of TP from the Athabasca River, most (94%) was from non-point sources with forested land being the largest contributor (Table 4.8). Agricultural land (fertilized cropland and unfertilized pasture land) contributed only 17% of the total TP export although this contribution is disproportionately high given that agricultural land covers only 3% of the basin. Since our estimate of TP export based on landuse patterns was comparable to observed values for the Athabasca River, we then attempted to assess whether fertilizer run-off contributes significantly to the nutrient load in the Athabasca River. Based on 2747 km^2 of fertilized land in the Athabasca drainage basin (Table 4.7), a fertilizer application rate 34 kg/ha/y P, and a 1% loss of applied P, we estimated that runoff from fertilizer application in the Athabasca River basin accounts for 93 tonnes/y P. This value is comparable to our estimates based on landuse and export coefficients of 116 tonnes/y TP exported from cropland in the Athabasca River basin. Similar calculations for the Wapiti River gave 70 tonnes/y P that is lost by runoff from fertilizer application, a value comparable to our estimate based on landuse and export coefficients of 79 tonnes/y TP exported from cropland. These findings support our contention that use of export coefficients and landuse patterns provide a reasonable estimate of TP export for the Athabasca River.

Our results showed that most of the TP load in the Athabasca and Wapiti rivers is from non-point sources. The predominance of non-point sources of P is likely true for the Smoky River and for TN for all three rivers. Caution must, however, be exercised when assessing the contribution of various sources to total loading of TP for the Smoky River and TN for the Athabasca and Wapiti rivers since, for these cases, predicted and observed loads did not closely match. Our observation on the importance of non-point sources, primarily forested land, to nutrient loading is consistent with observations for other drainage basins with moderate development. Thus, 7% of the TP export from the Fraser River, British Columbia, at Marguerite is from non-point sources (French and Chambers 1995). In contrast, non-point sources in heavily-developed European basins averaged 36, 26, 48 and 71% of the TP load and 53, 48, 52 and 79% of the dissolved inorganic N load near the mouths of the Rhine, Neckar, Main and Mosel rivers (1973-1987 data; Behrendt 1993). Similarly, in the Vistula River, Poland, nonpoint-source discharges contributed about 70% of the N and P load (Sundblad *et al.* 1994 from Rybinski *et al.* 1990) while in the Girou River, France, non-point sources accounted for about 39% of the TP load (Probst 1985).

In conclusion, our results showed that the use of export coefficients and landuse patterns provides a reasonable approach for estimating TP loads in the Athabasca and Wapiti rivers. In contrast to TP, TN and SRP loads for the Athabasca River could not be predicted from export coefficients and landuse patterns. It is unlikely that poor selection of TN and SRP export coefficients was a major source of error since measured coefficients for streams in northern Alberta were used in our calculations. Differences between predicted and observed loads may relate to differences in river discharge between years with bed-load transport of nutrients occurring during high flow years. Over-predictions of SRP export based on export coefficients and landuse patterns are also likely due to uptake of P by primary producers.

Our analysis of nutrient contributions also highlights the fact that data are almost entirely lacking on the contribution of non-point sources to nutrient loads in the Northern Rivers. While contributions can be estimated from the limited data for Alberta and from data for other parts of the world, the large changes in landuse patterns that have taken place and continue to occur in the boreal forest (e.g., in 1988, the Alberta government allocated 177000 km^2 for forestry, about 27% of the provincial forests and 50% of the green area (Dancik 1995)) may have substantial impacts on nutrient loading particularly to tributaries of the Peace and Athabasca Rivers.

5.0 GROUNDWATER CONTRIBUTIONS TO THE ATHABASCA RIVER DURING WINTER

5.1 INTRODUCTION

Simulation modelling of under-ice dissolved oxygen (DO) concentrations for the Athabasca River has been undertaken since the mid 1980's to elucidate the factors controlling DO and assist in establishing industrial operating licenses. One factor that could skew the results obtained from simulation modelling is the amount of groundwater entering the river system, since hydrologic components of most simulation models assume negligible net losses or gains from groundwater. Significant volumes of groundwater entering the system at localized sources could effectively alter predicted DO concentrations unless this source of groundwater was accounted for in the model. The purpose of this analysis was to determine if there were any large groundwater contributions to the Athabasca River during under-ice conditions (January-March). This was accomplished by examining flow budgets and ionic concentrations of the Athabasca River for the 1989 to 1993 winters to identify any unaccounted changes in discharge and ionic composition.

5.2 METHODS

5.2.1 Hydrologic Mass Balance

Flow budgets were calculated for the Athabasca River for late winter (February-March) for the reach from upstream of Hinton (i.e., near Entrance) to Fort McMurray. Discharge data for the Athabasca River upstream of Hinton and downstream of Fort McMurray were obtained from Alberta Environmental Protection (AEP) and Water Survey of Canada (WSC), respectively. In addition, discharge data for all major tributaries were obtained from AEP. Upstream (Athabasca River upstream of Hinton) and tributary discharges were summed and expressed as a percentage of total discharge for the Athabasca River downstream of Fort McMurray.

5.2.1 Dominant Ion Chemistry

Surface-water systems such as rivers are supplied with water from a direct run-off fraction that enters through precipitation and a base-flow fraction made up of groundwater that infiltrates into the channel. This base-flow fraction often has a greater dissolved solids concentration than the run-off fraction due to the increased residence time in the groundwater reservoir (Hem 1985). Therefore, large, localized groundwater inputs to the Athabasca River mainstem may increase the concentrations of dissolved solids in the mainstem water downstream of the input. This would be especially apparent in constituents such as sodium (Na) or calcium (Ca) which are highly soluble and tend to remain in aqueous solution.

Groundwater contributions would also be more apparent during periods of low flow (January-March for the Athabasca River), due to the decreased surface-water to groundwater ratio.

To identify sites of groundwater inputs, dissolved solid concentrations (% milliequivalents per litre for the major anions and cations) were examined for the Athabasca River from upstream of Hinton to Big Point Channel, 1239 km downstream for the period of late winter (February-March). Mainstem, tributary and effluent (point-source) stations were sampled for the 1989 to 1993 winters by AEP in a downstream order at time intervals corresponding to the water time-of-travel. Sampling and analytical methods are described by Noton and Shaw (1989). Mainstem sites were compared to tributary and effluent sites to determine if any changes in the ionic composition of the mainstem were due to known (i.e., tributaries or effluent) or unknown (i.e., groundwater) inputs.

5.3 RESULTS AND DISCUSSION

5.3.1 Hydrologic Mass Balance

The sum of the upstream and tributary flows ranged from 66 to 106% of total discharge at Fort McMurray in February-March 1989 to 1993 (Table 5.1). The percentage of downstream discharge accounted for by known sources (tributaries and headwaters) was, on average, 86%. The unaccounted discharge could be due to additional inputs to the system from ungauged tributaries or groundwater. Given that unaccounted discharge is, on average, less than 15% of the flow at Fort McMurray in February-March, it is unlikely that there are large unknown sources of input contributing to the total discharge of the Athabasca River in late winter. Groundwater input could contribute the unaccounted for 15%, however given that discharge data were not available for small tributaries and the difficulties in measuring discharge under ice, any groundwater contribution to the mainstem is likely only a small percentage of river discharge.

5.3.2 Dominant Ion Chemistry

Calcium and carbonate+bicarbonate are the dominant ions in the Athabasca River (Figure 5.1). Carbonate + bicarbonate are grouped together since their concentrations are co-dependent. Sulphate and magnesium are the next dominant ions, except at the furthest downstream site where Na+K are more abundant. Chloride comprises the smallest fraction of the major ion pool (<2%) at all sites except the furthest downstream site.

The ionic composition of the mainstem water along the length of the river was similar for all winters (Figures 5.2-5.11). The proportion of Na+K increased with distance downstream with sharp increases at the following sites: Athabasca River at Obed Coal bridge, Athabasca River 10 km downstream of McLeod River, and Athabasca River upstream of Suncor. These increases are all associated with either point-source effluent inputs, tributary inputs, or both. Thus the proportion of Na+K increased below the

Table 5.1 **Surface-water discharge to and downstream of the Hinton-Fort McMurray reach of the Athabasca River for late winter (February-March), along with percent of downstream flow accounted for by surface-water inputs. Discharge data were obtained from the Alberta Environmental Protection winter water quality surveys except for discharge downstream of Fort McMurray which was obtained from Water Survey of Canada.**

Source	Discharge (m^3/s)				
	1989	1990	1991	1992	1993
(a) Athabasca R. above Hinton	28	33	52	47	29
Tributary inflows between Hinton and Fort McMurray	63	136	92	97	71
(b) Fort McMurray	138	198	150	135	129
Hinton and tributary discharge (a) as a percent of Fort McMurray discharge (b)	66%	86%	96%	106%	78%

Hinton pulp mill and sewage inputs (Figures 5.2-5.6). Increases were also associated with the Millar Western pulp mill and Whitecourt sewage outfalls (Figures 5.2-5.6). Both the Hinton and the Millar Western effluents are dominated by Na+K (Figures 5.2-5.6). However, despite high proportions of Na+K, the load to the river is small due to the low flow associated with these anthropogenic inputs (Figure 5.12); thus the proportional increase in Na+K in the mainstem is small. In addition to effluent and tributary effects, there is a gradual increase in Na+K between approximately 250 and 950 km downstream. This may be due to inputs from small, diverse groundwater sources, ungauged tributaries or erosion. Effluent from the Town of Athabasca is dominated by Na+K; however, there is no corresponding increase in the mainstem levels. This is probably due to the fact that this input has a very low discharge and thus low loads (Figure 5.12). The only other increase in mainstem Na+K occurs in the Fort McMurray area and is undoubtedly due to the large Na+K dominated input from the Clearwater River (Figures 5.2-5.6 and Figure 5.12). Calcium and magnesium levels decreased over the river length and did not show any sharp increases (Figures 5.2-5.6).

Anionic composition in the Athabasca River was similar along the length of the river for all winters (Figures 5.7-5.11). There is an initial increase in chloride (Cl) levels associated with the Cl dominated input from the Weldwood pulp mill. The only other increase in Cl ions is associated with the Clearwater River and the Fort McMurray and Suncor effluents. The Clearwater river has a large influence because of its high flow (Figure 5.12) and high Cl levels. Hamilton *et al.* (1985) also noted similarly high Cl levels in the Clearwater River in 1984/85. Sulphate levels decreased over the river length and did not show any sharp increases (Figures 5.7-5.11). Bicarbonate+carbonate levels increased between approximately 50 and 250 km downstream due to high concentrations associated with tributary and effluent sources in this area (Figures 5.7-5.11). The levels decrease again approximately 950 km downstream. Bicarbonate+carbonate levels are higher in most of the tributary sources than the mainstem yet there is no apparent increase in mainstem levels (Figures 5.7-5.11). Thus, it is unlikely that any groundwater inputs would be reflected in the mainstem bicarbonate+carbonate levels.

Based on the analysis of flow budgets and ionic composition of the Athabasca mainstem, there does not appear to be any large localized inputs of groundwater to the system during late winter. Since changes in ionic composition are apparent with inputs from point-source discharges, we could detect changes in composition due to groundwater inputs if concentrations were similar and flows equal to or greater than those of point-source inputs (0.01-1.0 m^3/s). Groundwater inputs should be more apparent during the low flow periods (February-March) studied here, so it is unlikely that there are large localized inputs of groundwater.

Figure 5.1 The proportion of calcium, carbonate+bicarbonate, sulphate, magnesium, sodium+potassium and chloride (expressed as % milliequivalents per litre) in the Athabasca River, Alberta for the 1989 to 1993 winters. Data from the Alberta Environment winter water quality surveys.

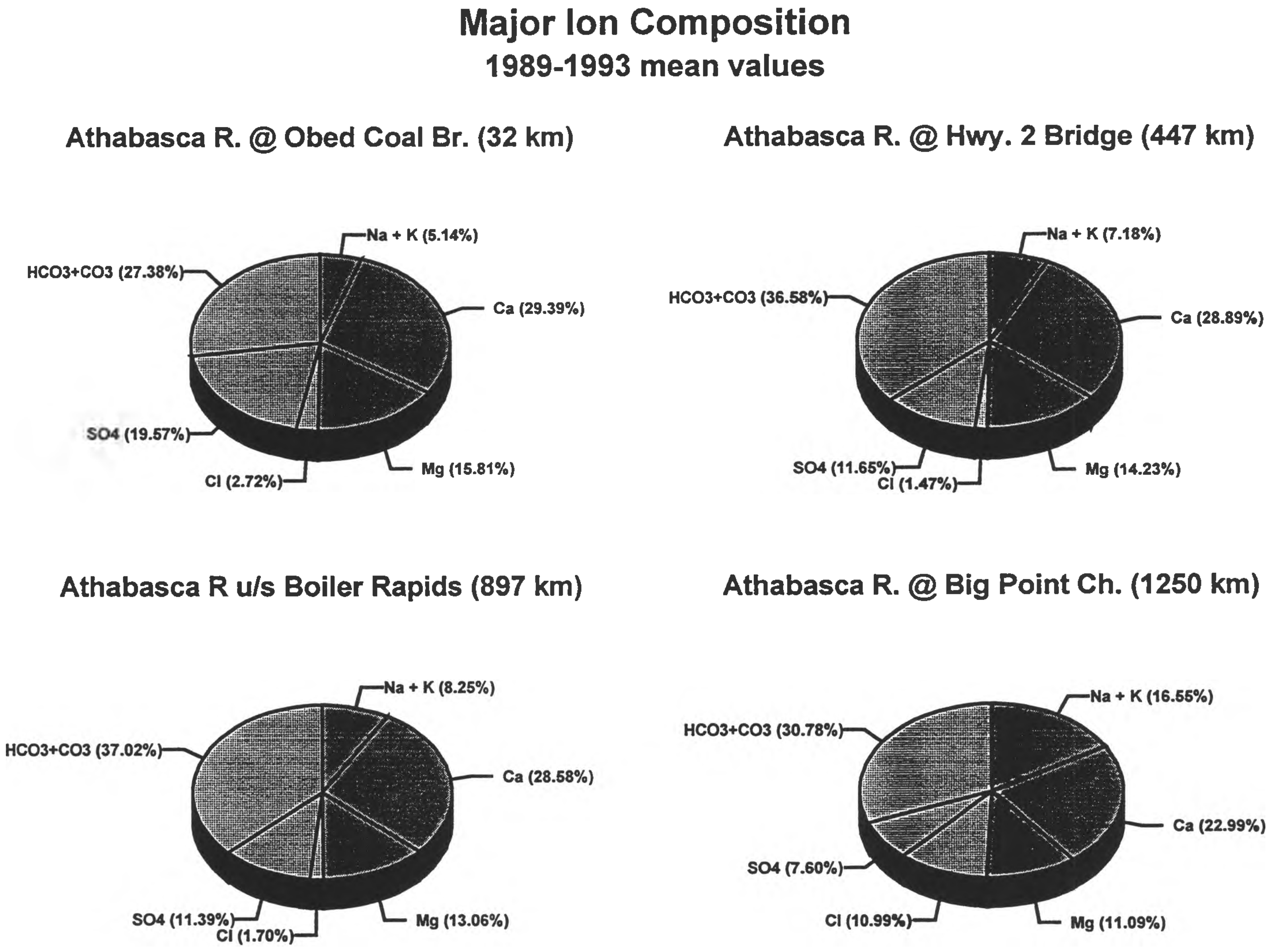


Figure 5.2 Cationic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1989. Data from the Alberta Environment winter water quality surveys.

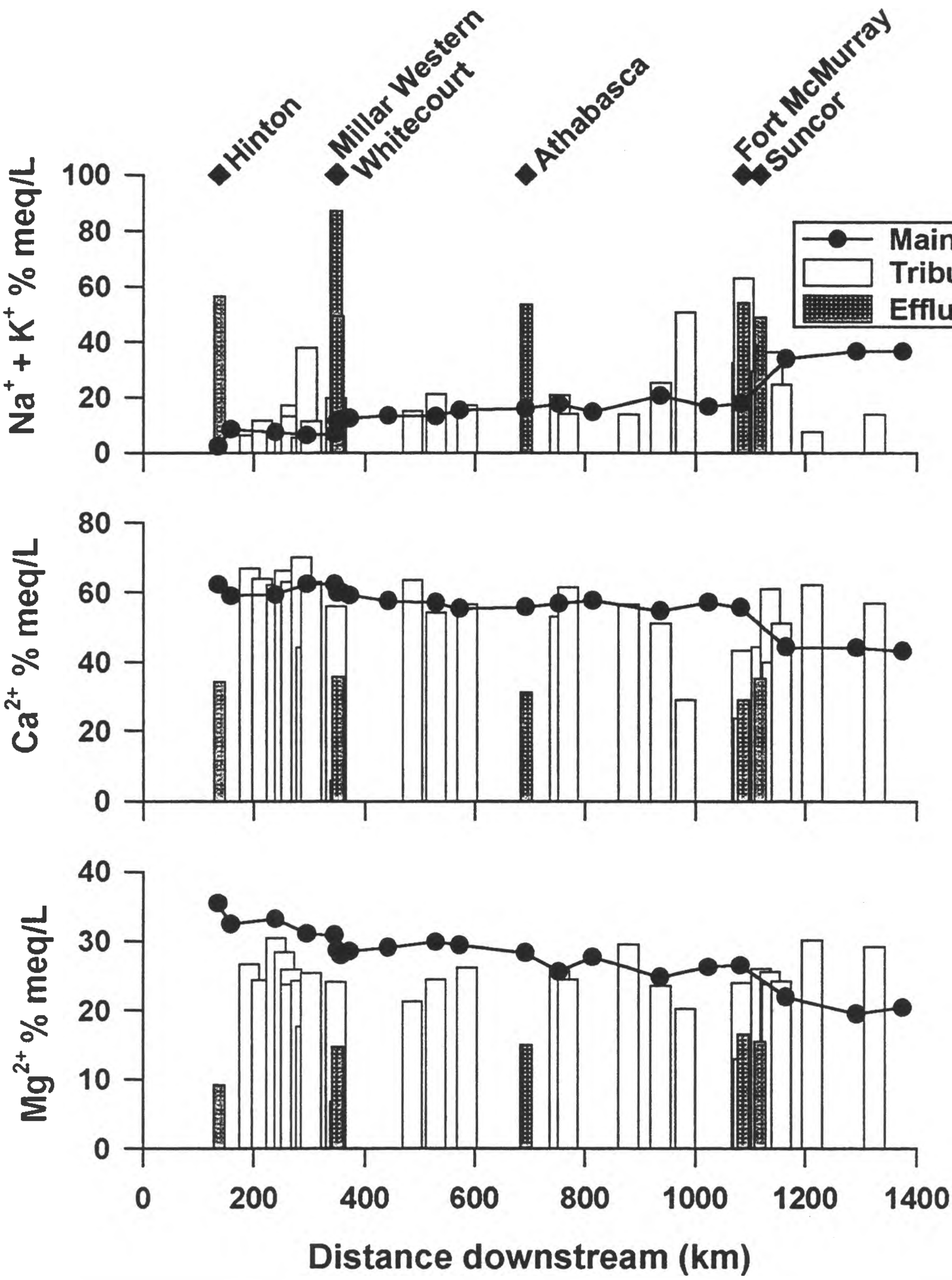


Figure 5.3 Cationic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1990. Data from the Alberta Environment winter water quality surveys.

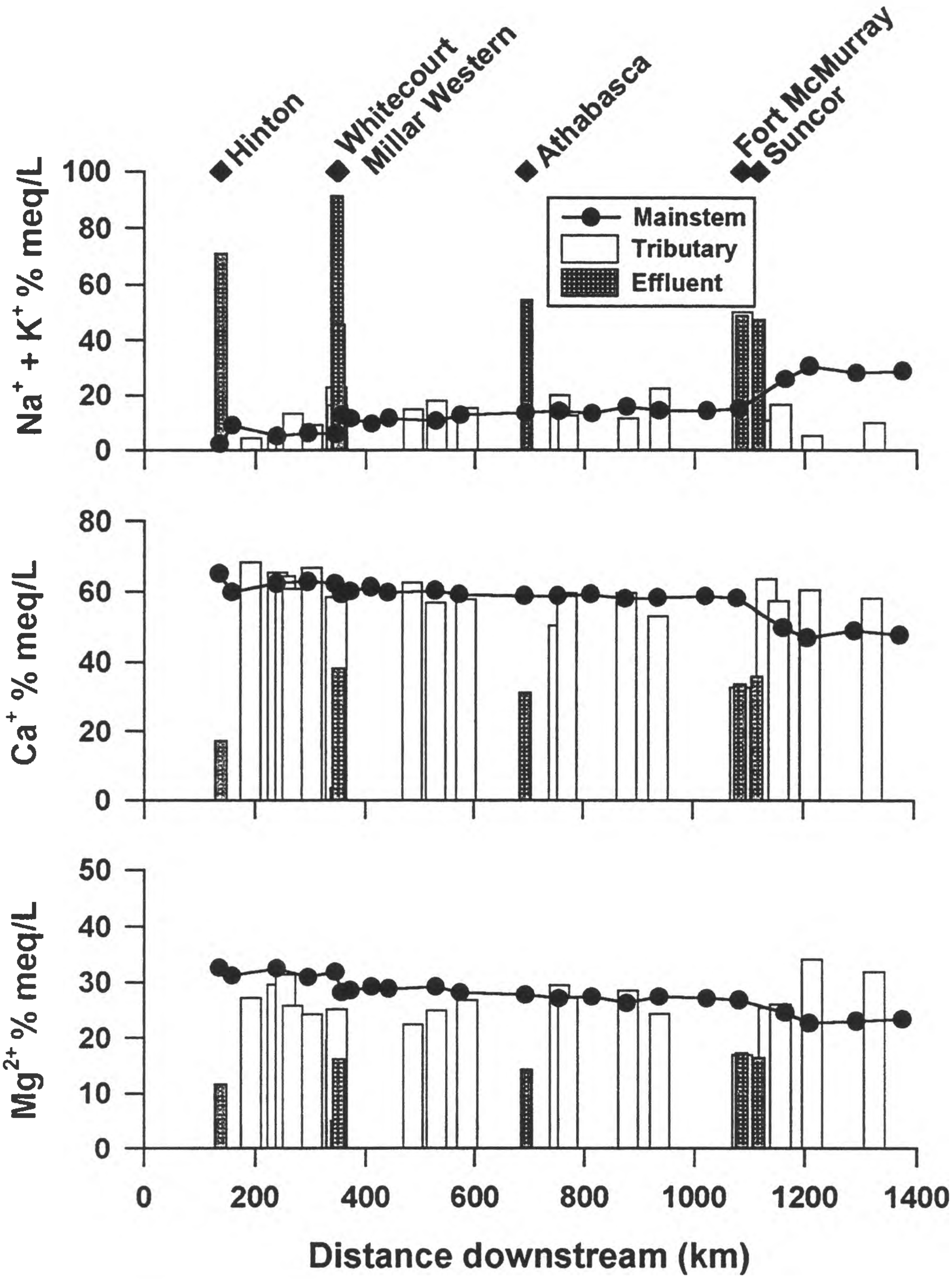


Figure 5.4 Cationic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1991. Data from the Alberta Environment winter water quality surveys.

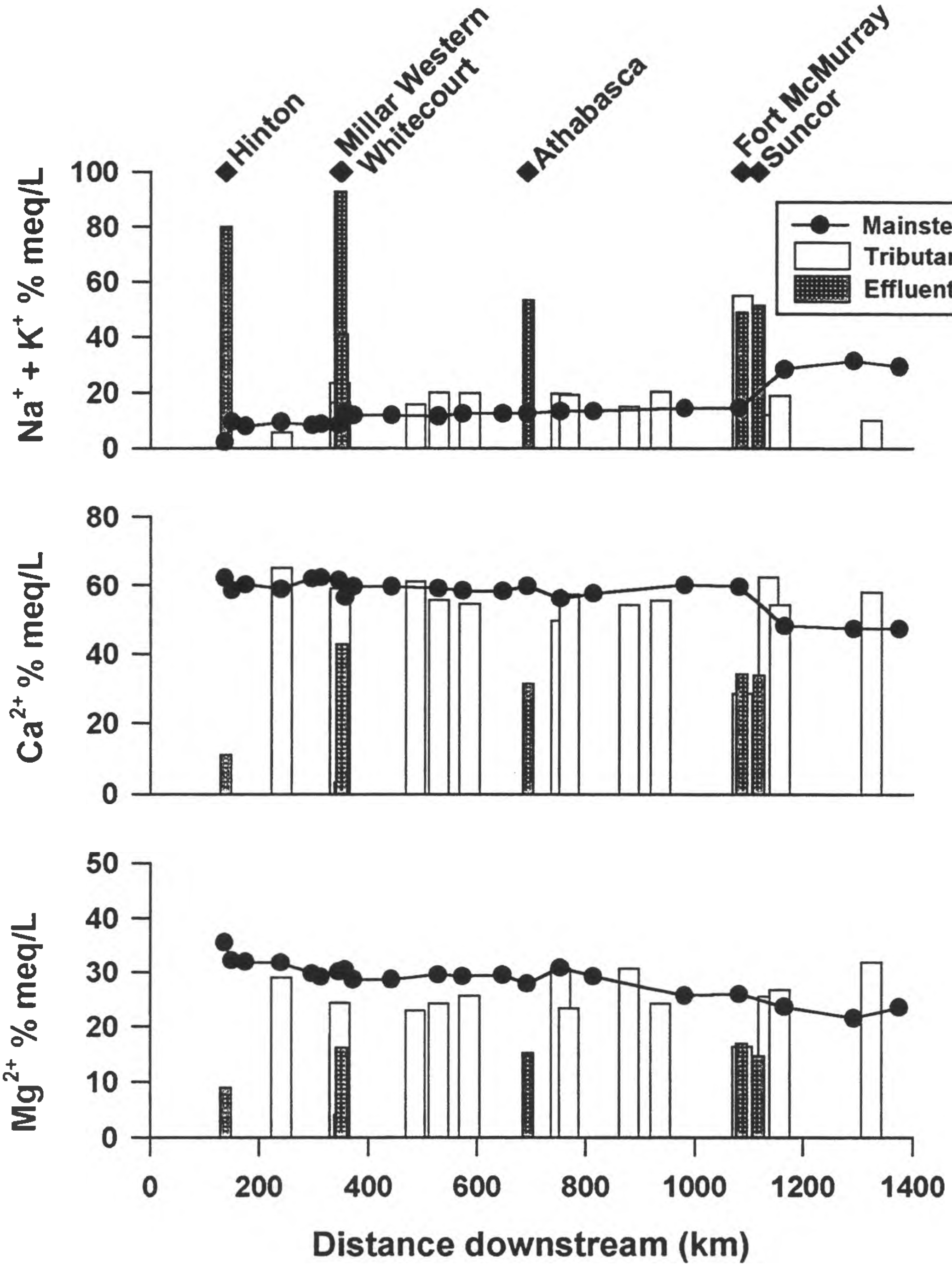


Figure 5.5 Cationic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1992. Data from the Alberta Environment winter water quality surveys.

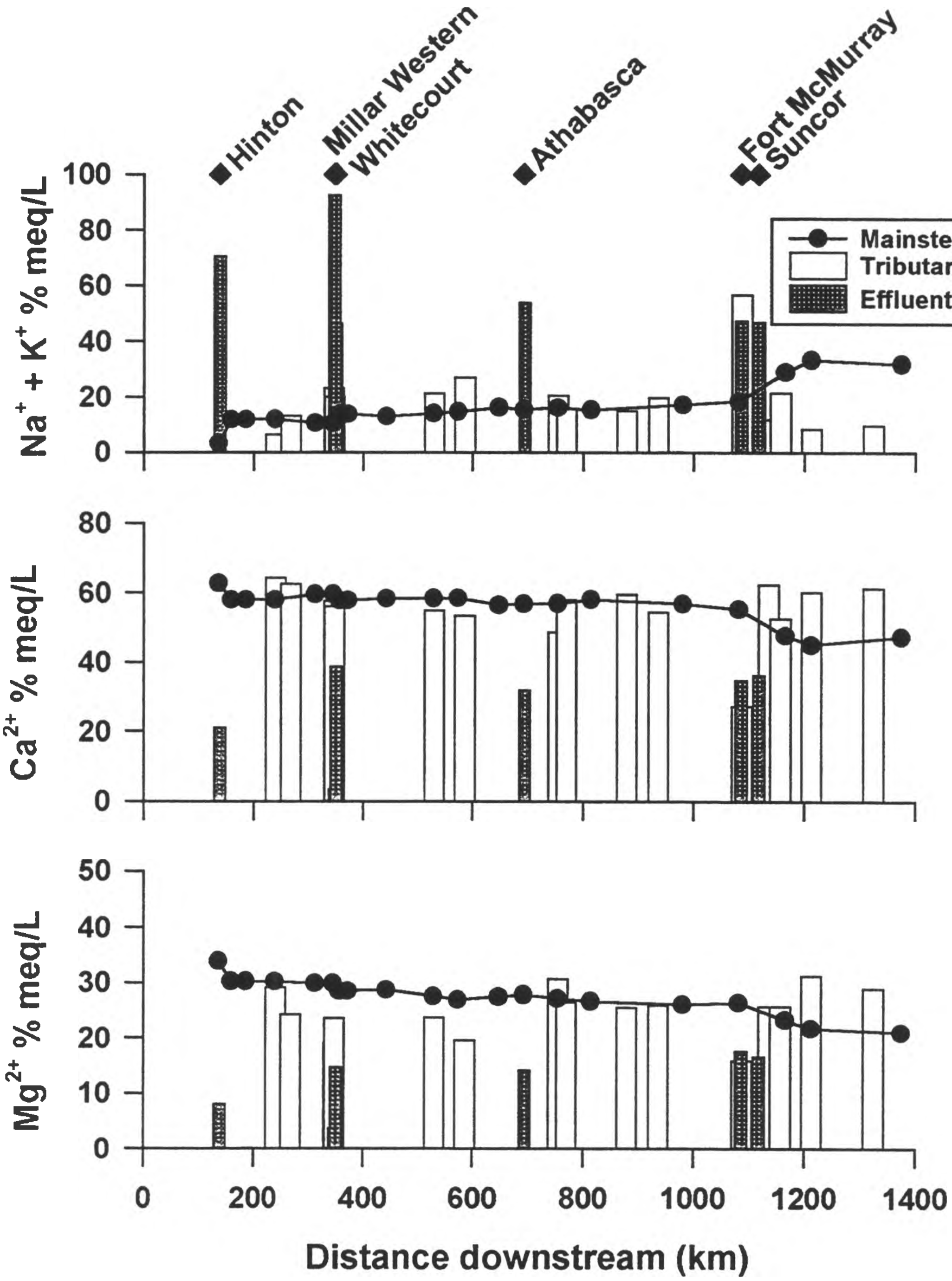


Figure 5.6 Cationic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1993. Data from the Alberta Environment winter water quality surveys.

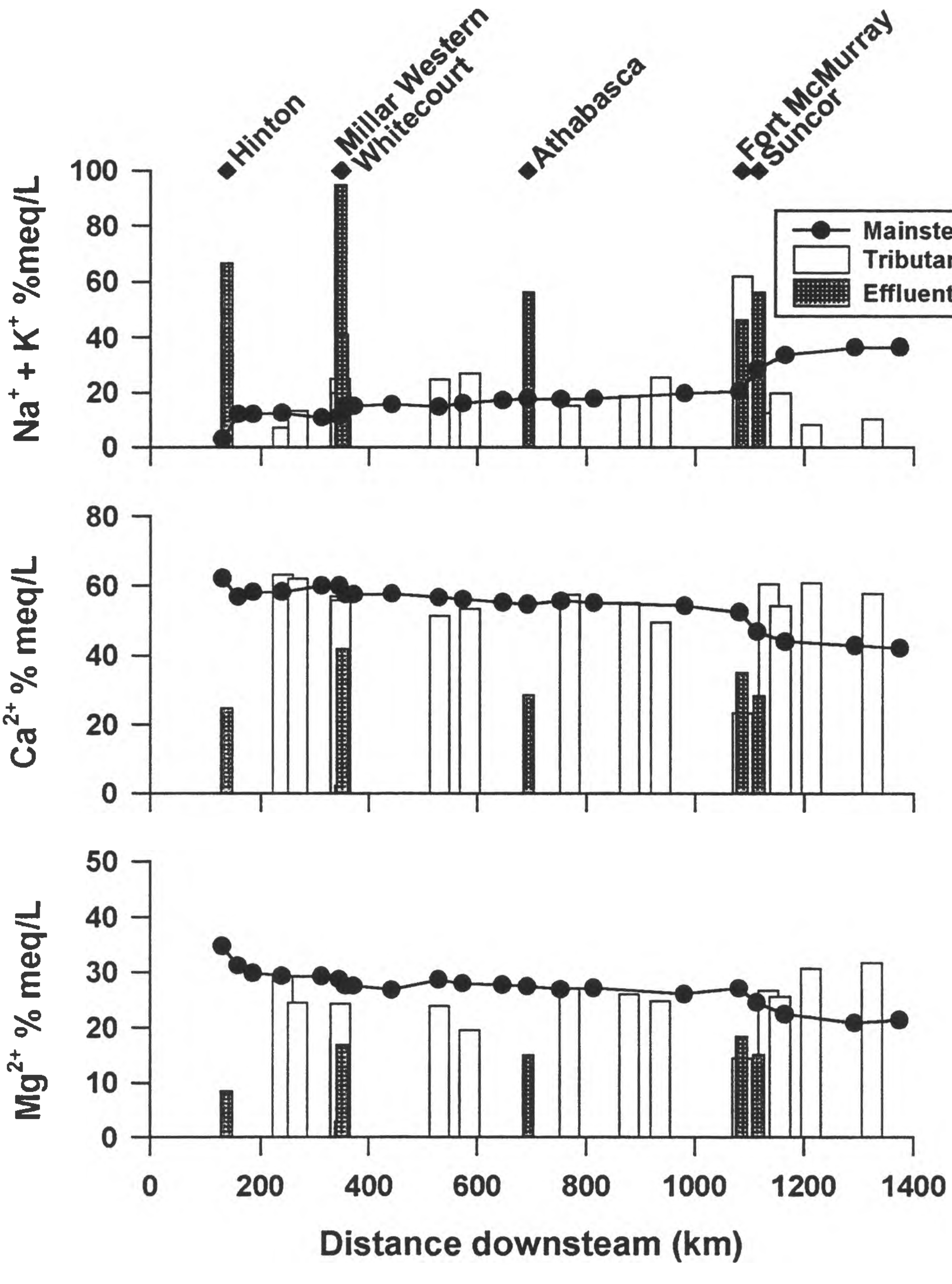


Figure 5.7 **Anionic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1989. Data from the Alberta Environment winter water quality surveys.**

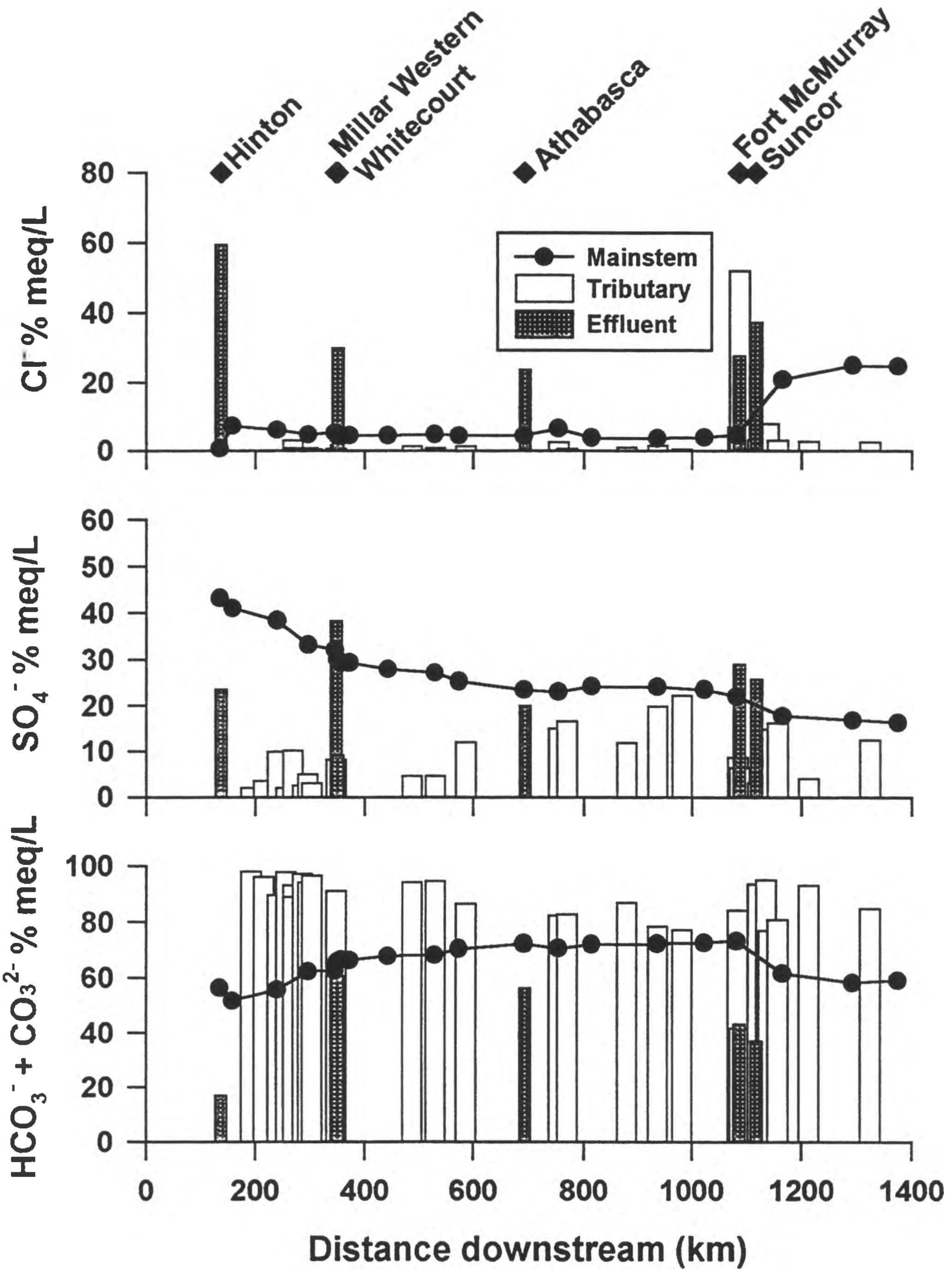


Figure 5.8 Anionic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1990. Data from the Alberta Environment winter water quality surveys.

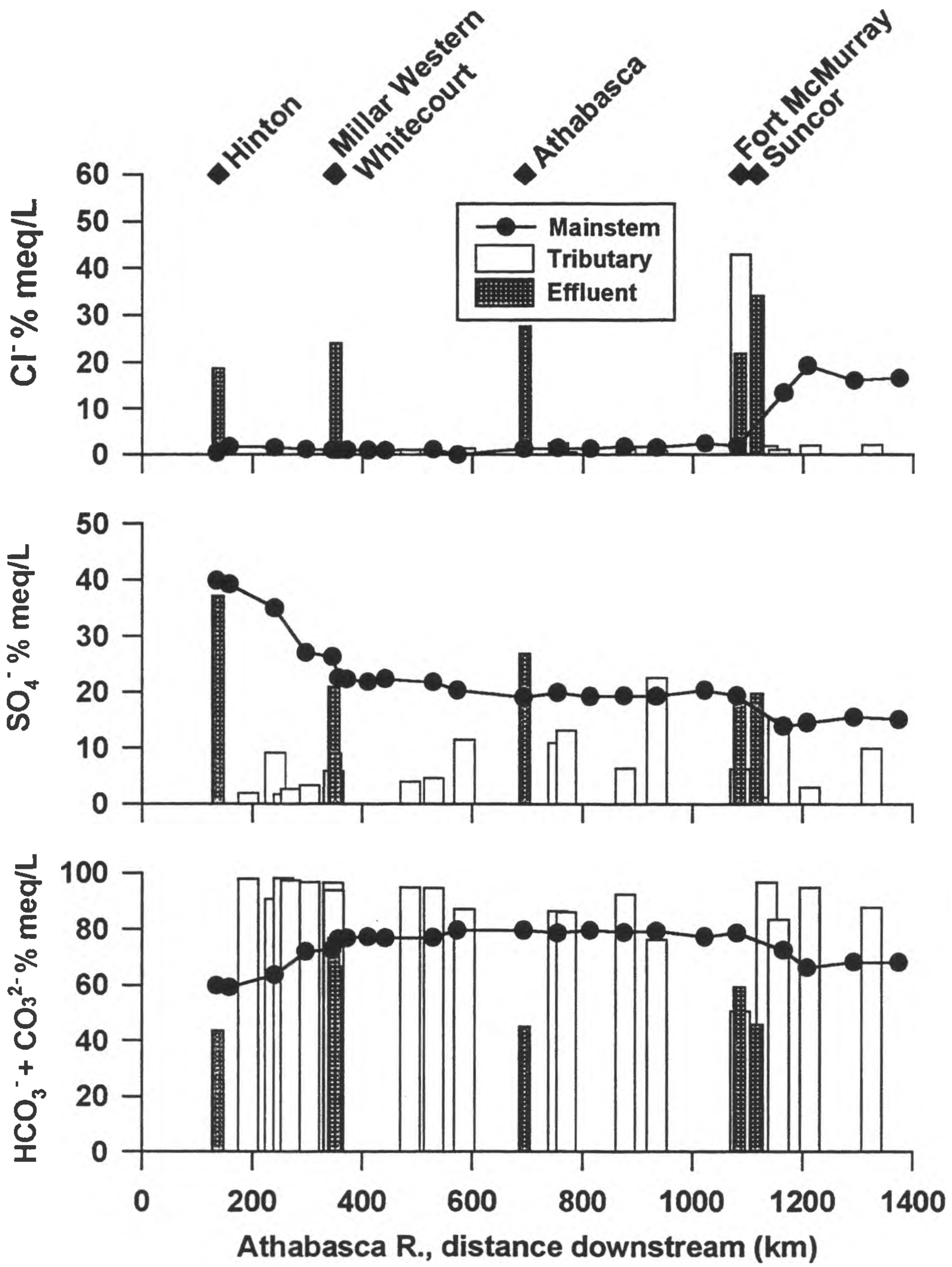


Figure 5.9 **Anionic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1991. Data from the Alberta Environment winter water quality surveys.**

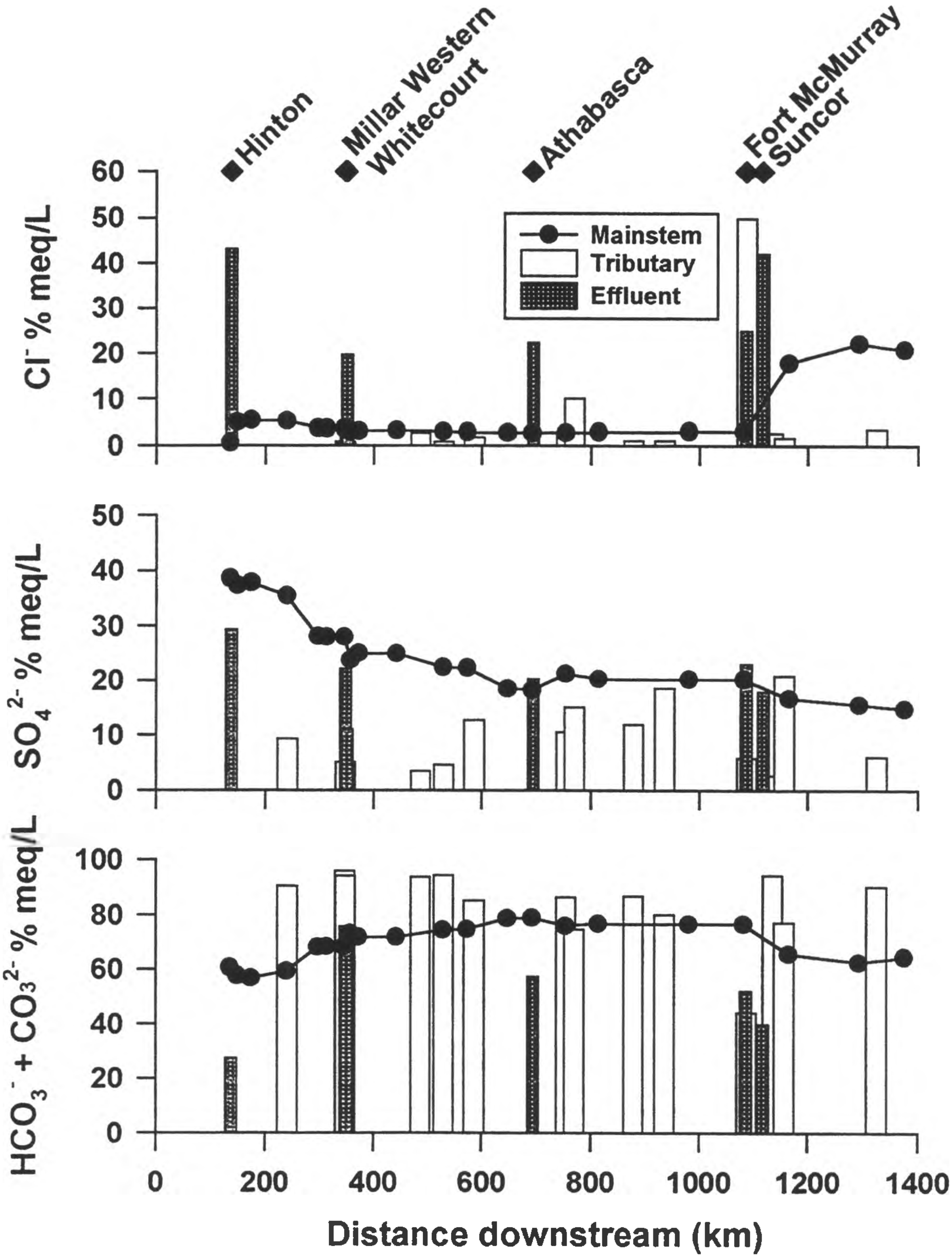


Figure 5.10 **Anionic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1992. Data from the Alberta Environment winter water quality surveys.**

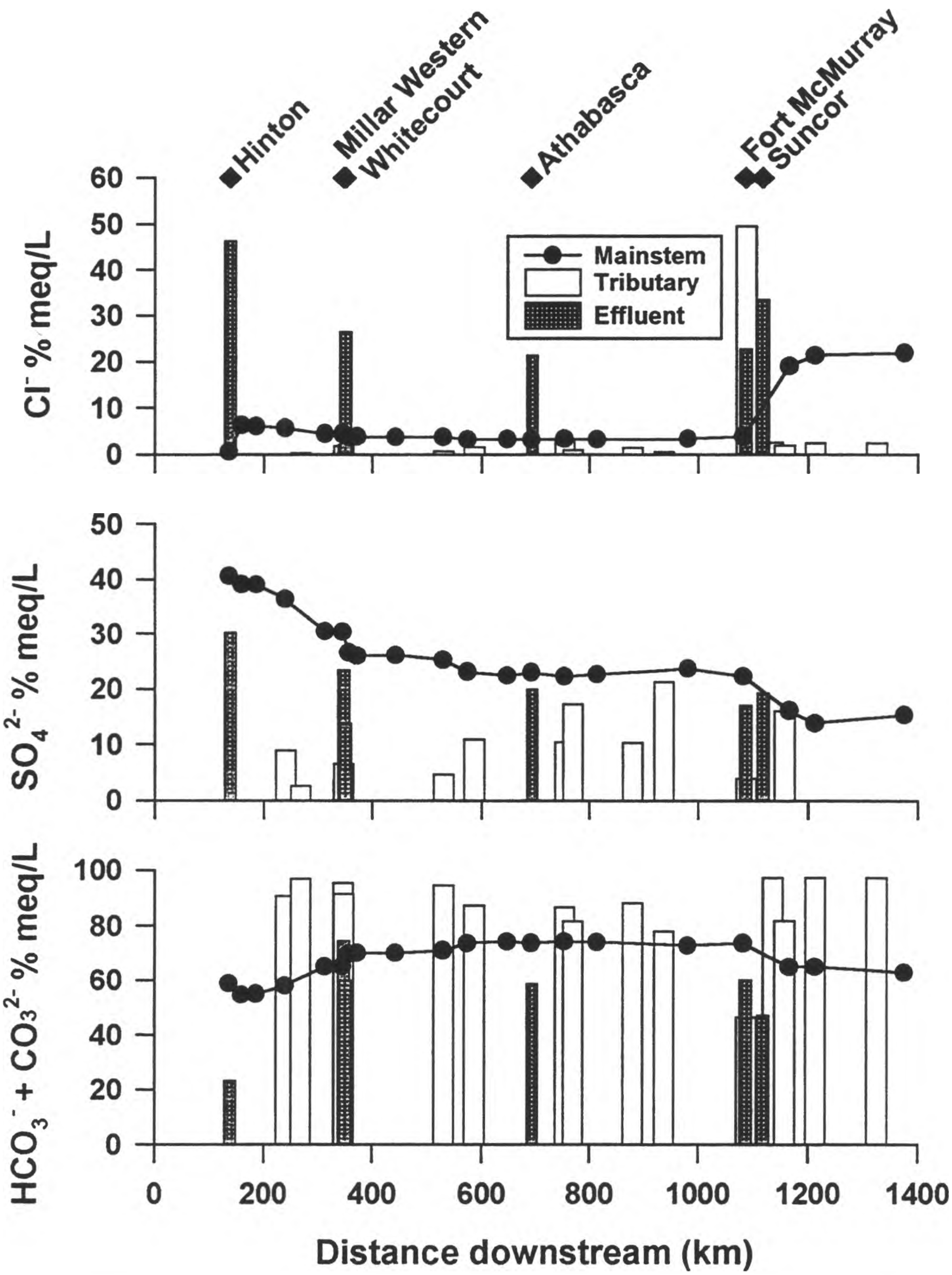


Figure 5.11 Anionic composition (expressed as % milliequivalents per litre) of the Athabasca River, Alberta for winter 1993. Data from the Alberta Environment winter water quality surveys.

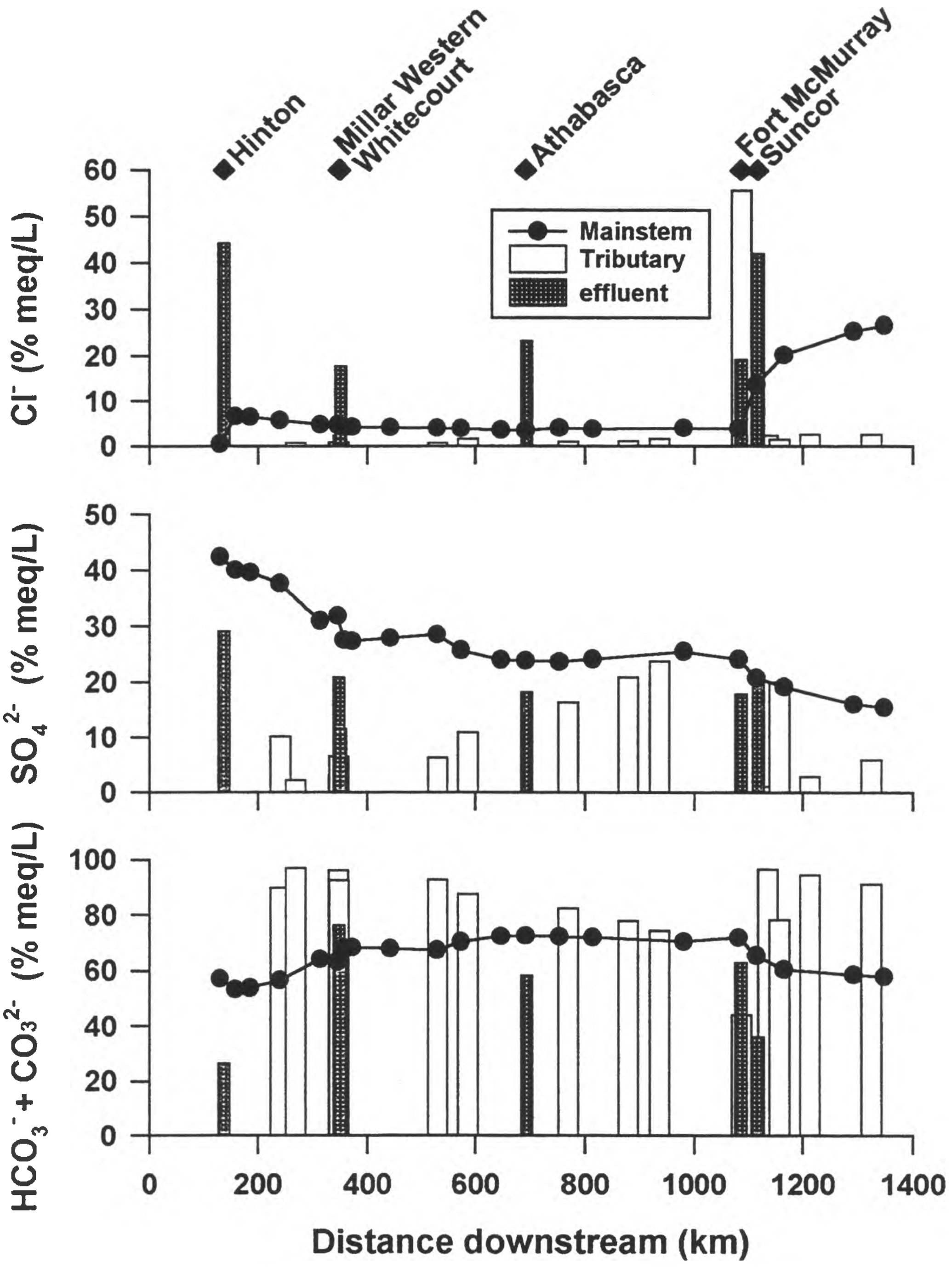
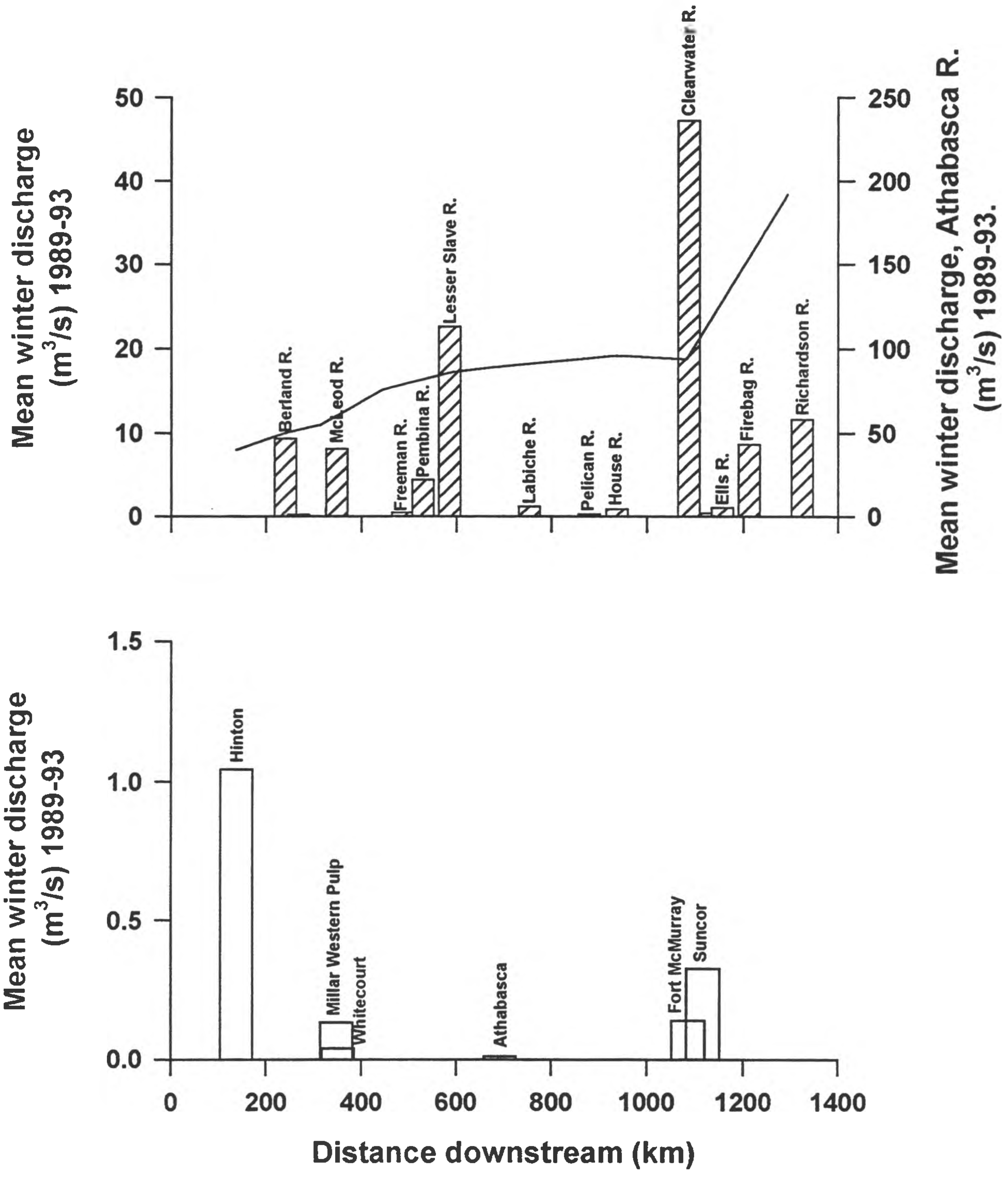


Figure 5.12 Mean winter (February-March, 1989-1993) discharge for the Athabasca River (solid line), tributaries to the Athabasca River (hatched bars) and continuous point-source discharges to the Athabasca River (open bars). Only sites with three or more data points were used to determine mean discharge values. All data are from the Alberta Environment winter water quality surveys.



6.0 CONCLUSIONS AND RECOMMENDATIONS

Analysis of long-term (1980 or 1989 to 1993) median values of TP and TN from 10 sites showed that nutrient concentrations varied along the length of the Athabasca River with TP and TN concentrations lowest upstream of the Town of Jasper, and increasing between Jasper and Hinton and, again, downstream of Hinton. Thereafter, TN concentrations increased steadily along the river to Fort McMurray while TP concentrations returned to background levels 170 km downstream of Hinton, increased downstream of Whitecourt, and then remained relatively constant along the remainder of the river. Of the 721 TP measurements from Athabasca River between 1980-1993, 146 measurements or 20% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP of 0.05 mg/L P. Most of these exceedances occurred during summer and were likely due to high particulate P concentrations. The *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by only 2% of the samples. Continuously-discharging industrial and municipal sources contributed 6 to 16% of the TP and 4 to 10% of the TN load on an annual basis. With the exception of Jasper, municipal sources contributed < 2% of the annual TP and TN loads. However, during low flows, point sources contributed 37% of the TP load (27% from pulp mills and 10% from municipalities) and 13% of the TN load (7% from pulp mills and 5% from municipalities) at Old Fort. Most of the non-point source TP and TN load was derived from runoff from forested land. TP losses from cropland were estimated to be less than 10% of the load from forested land.

In the Wapiti River, median annual TP and TN concentrations increased from upstream of Grande Prairie to the river mouth; concentrations were lower in the Smoky River at Watino than at the mouth of the Wapiti River. Of the 27 TP measurements at the mouth of the Wapiti River, 20 measurements or 74% of the samples exceeded the *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TP of 0.05 mg/L P. The fact that the percent of exceedances increased from 12 to 74% from upstream of Grande Prairie to the mouth of the Wapiti River suggests that P from the City of Grande Prairie and Weyerhaeuser Canada Ltd. effluents contributed to non-compliance with the TP guideline. The *Alberta Surface Water Quality Objective* (Alberta Environment 1977) for TN of 1.0 mg/L N was exceeded by 19% (n=26) of the samples from the Wapiti River near the mouth compared to no TN exceedances (n=21) for samples from upstream of Grande Prairie, again suggesting that exceedances are related to nutrient loading from the Grande Prairie STP and mill. The Grande Prairie sewage treatment plant and the Weyerhaeuser pulp mill contributed 10 and 13%, respectively, of the TP load and 7 and 13%, respectively, of the TN load to the Wapiti River on an annual basis. However, during low flows, point sources contributed 41% of the TP load (24% from the pulp mill and 18% from Grande Prairie) and 34% of the TN load (22% from the pulp mill and 12% from Grande Prairie) in the Wapiti River. TP losses from cropland (79 tonne/y) were similar to losses from forested land (109 tonne/y) in the Wapiti River basin.

Examination of flow budgets and ionic composition of the mainstem surface waters of the Athabasca River for the 1989 to 1993 winters indicated that for most winters, it is unlikely that there are large localized inputs of groundwater. Comparison of the sum of headwater and tributary flows with the measured flow at Fort McMurray showed that the percentage of downstream discharge accounted for by known sources was, on average, 86% (66 to 106% range). While this unaccounted discharge may be due to groundwater inputs, some of this discrepancy is undoubtedly due to difficulties in measuring discharge under-ice cover. Similarly, there were no changes in ionic proportions that could not be attributed to effluent or tributary inputs. These results indicate that large localized inputs of groundwater during winter were unlikely.

While pulp and paper mills contribute 4% of the annual TP load in the Athabasca River at Old Fort and 2% of the annual TP load in the Smoky River near Watino, their nutrient loading still produces ecological consequences. Increased periphyton growth has been observed in fall downstream of Jasper, Hinton, Whitecourt, Athabasca, Fort McMurray and Grande Prairie. The effect of enhanced periphyton production due to effluent loading has been transferred to higher trophic levels in the food web with benthic invertebrate communities downstream of all pulp mill discharges showing increased densities. These nutrient impacts on riverine biota are due to the substantial contribution of nutrients from pulp mills and certain sewage discharges (e.g., Grande Prairie) during low flows. In addition, the bioavailable forms of N and P (which are responsible for increased aquatic plant growth) are proportionately more abundant in pulp mill and municipal effluents than in natural inflows. This means that our calculations based on total N and P loading would underestimate the contribution of pulp mills and municipalities to the rivers' bioavailable nutrient loads. Our analysis of N and P contributions also highlights the fact that data are almost entirely lacking on the contribution of non-point sources to nutrient loads in the Northern Rivers. While contributions can be estimated from the limited data for Alberta and from data for other parts of the world, the large changes in landuse patterns that have taken place and continue to occur in the boreal forest (e.g., agricultural land clearing, timber harvesting, oil and gas activities) may have substantial impacts on nutrient loading particularly to tributaries of the Peace and Athabasca Rivers.

The following recommendations are proposed:

•Regular monitoring and reporting of nutrients from sewage treatment plants should be license requirements, particularly the larger sewage treatment plants such as Grande Prairie and Fort McMurray. These larger sewage treatment plants have nutrient loads similar to that of pulp mills in the basins. Yet under the 1993 *Alberta Environmental Protection and Enhancement Act*, operators of continuously-discharging sewage treatments plants need only report exceedances (within 24 h) to Alberta Environmental Protection.

•Bioavailability of nutrients in industrial and municipal effluents should be characterized. At present, pulp mill licensing requirements include monitoring of NH_4, NO_3, NO_2, total Kjeldahl N, TDP and TP in weekly grab samples; there is not a monitoring requirement for nutrients by municipal dischargers. Analysis of SRP concentrations and/or algal bioassays for N and P availability in effluents would allow better assessment of instream impacts.

•Data are almost entirely lacking on the contribution of non-point sources to nutrient loads in the Northern Rivers. While contributions can be estimated from the limited data for Alberta and other parts of the world, the large changes in landuse patterns that have taken place and continue to occur (e.g., agricultural land clearing, timber harvesting, oil and gas activities) warrant closer examination of the impacts of changing landuse on nutrient loading.

- *Alberta Water Surface Quality Objectives* (Alberta Environment 1977) are frequently exceeded for TP and occasionally exceeded for TN in the Athabasca, Wapiti, Smoky and Peace rivers. With the exception of the Wapiti River, many of these exceedances are attributable to high particulate loads associated with high flows. In the Wapiti River, many of the exceedances appear attributable to effluent discharge from Weyerhaeuser Canada Ltd. and, in the case of TP, to the Grande Prairie sewage treatment plant. Effluent permit limits for nutrients need to be applied on a case by case basis to ensure that effluents do not cause receiving waters to be of poorer quality than recommended by provincial water quality objectives.

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APPENDIX A. Terms of Reference For Contract

NORTHERN RIVER BASINS STUDY
TERMS OF REFERENCE

Project 2622-D1: **The Contribution of Anthropogenic Sources to the Athabasca River Nutrient Load**

I. Background and Purpose

Preliminary estimates of the relative contributions of phosphorus from pulp mills to the total phosphorus budget for the Athabasca River were previously calculated by the NRBS (NRBS Project # 2601-B1). To estimate total loads of phosphorus in the river, sub-basins within the Athabasca River basin were designated as either forested or mixed forest-agriculture and the area of each sub-basin was multiplied by a phosphorus export coefficient (kg TP/km^2/yr) obtained for either forested or mixed forested-agricultural lands. Since the initial calculations were undertaken, several questions have been raised:

(1) The phosphorus export calculations to date have been based on TP and not bioavailable forms of phosphorus, yet the proportion of bioavailable P in the TP load from pulp mills and sewage treatment plants is much greater than the proportion in natural TP loads.
(2) Can the export coefficients that were used in the original calculations be applied to basins that are considerably smaller or larger than the basin for which they were derived? In other words, is there a scaling factor that must be applied when using export coefficients?
(3) The sub-basins were originally designated as either forested or mixed. Given current GIS capabilities, can we obtain more accurate estimates of the area within each basin that is forested, agricultural or mixed?
(4) Phosphorus export coefficients provide estimates of annual loads. What is the contribution of nutrients from pulp mills to the total load on a seasonal basis?
(5) What is the contribution of anthropogenic non-point sources, specifically agricultural?

The purpose of this project is to address these questions and produce a better estimate of the contribution of anthropogenic point-sources to the total load of nutrients in the Athabasca River.

II. Requirements

1. Obtain better estimates of the relative contribution of point-source anthropogenic inputs to the nutrient load in the Athabasca River by:

   (a) obtaining accurate estimates of the area within each sub-basin of the Athabasca River that is forested, agricultural land or mixed forested-agricultural through use of the NRBS GIS facilities,

(b) assessing wether the export calculations used in previous estimates of nutrient loads in the Athabasca River need to be scaled according to the size of the basin to which they are applied, and

(c) obtain estimates of export coefficients for the bioavailable forms of phosphorus and, if possible, nitrogen.

(2) Obtain potential loads of N and P from agricultural sources by estimating fertilizer application to each of the sub-basins within the Athabasca River using the NRBS GIS facilities.

(3) Estimate the contribution of groundwater to discharge in the Athabasca River during winter.

III. Reporting Requirements

(1) Prepare a comprehensive report documenting the contribution of point-source, anthropogenic inputs, particularly pulp mill effluents, to the nutrient load in the Athabasca River.

(2) Ten copies of the draft report are to be submitted to the Component Coordinator by March 31, 1995.

(3) Three weeks after the receipt of review comments on the draft report, the contractor is to submit ten cerlox bound copies and two unbound, camera-ready originals of the final report to the Component Coordinator. An electronic copy of the report, in Word Perfect 5.1 format, is to be submitted to the Project Liaison Officer along with the final report. The style and format of the final report is to conform to that outlined in the NRBS Style Manual. A copy of the Style Manual will be supplied to the contractor by the NRBS.

IV. Project Administration

The Scientific Authority for this project is:

Dr. Patricia Chambers
National Hydrology Research Institute
11 Innovation Blvd.
Saskatoon, Saskatchewan, S7N 3H5
phone: (306) 975-5592
fax: (306) 975-5143

Questions of a scientific nature should be directed to her.

The NRBS Study Office Component Coordinator for this project is:

Greg Wagner
Office of the Science Director

Northern River Basins Study
690 Standard Life Centre
10405 Jasper Avenue
Edmonton, Alberta
T5J 3N4
phone: (403) 427-1742
fax: (403) 422-3055

Administrative questions related to this project should be directed to him.

APPENDIX B. **Summary statistics for total phosphorus (TP) and total nitrogen (TN) concentrations and discharge for municipalities and pulp mills in the Northern River basins. Municipal nutrient data from Alberta Environmental Protection winter water quality surveys (1988-1993) and database of D. Prince and S. Stanley (University of Alberta, Department of Civil Engineering). Municipal discharge data from the NRBS *Municipal and Non-Pulp Mill Industrial Effluents Database* (Sentar Consultants Ltd. 1995). Pulp mill data from the Northern River Basins Study database *Northdat* (McCubbin and AGRA Earth and Environmental 1995).**

Station	TP (mg/L)			TN (mg/L)			Discharge (m^3/d)		
	mean	SE	N	mean	SE	N	mean	SE	N
Municipal Sewage									
Athabasca	4.82	0.35	23	25.93	1.07	23	952	10	39
Barrhead	7.32	0.63	14	22.85	2.36	15			
Beaverlodge	3.34	0.34	10	16.78	2.25	10			
Berwyn	2.35	0.83	3	8.39	3.08	3			
Bluesky	0.86	0.3	3	3.3	1.35	3			
Boyle	2.11	0.71	3	7.27	2.15	3			
Debolt	4.60	1.28	3	16.67	4.65	3			
Desmarais	0.98	0.33	4	10.27	0.93	4			
Eaglesham	5.77	1.08	8	18.59	3.18	8			
Edson	4.10	0.3	12	15.33	1.53	12	3955	312	34
Entwistle	5.38	0.38	12	25.46	2.21	12			
Evansburg	6.08	0.63	3	9.07	3.38	3			
Fairview	1.84	0.48	4	10.48	2.99	4			
Fort McMurray	1.90	0.2	13	24.59	1.01	13	14000	393	17
Fort Vermillion	3.08	0.96	4	13.35	3.99	4			
Fox Creek	3.51	0.87	5	9.53	4.02	5			
Grande Cache	3.99	0.56	13	15.9	2.07	13	2032	59	39
Grande Prairie	4.97	0.16	73	23.2	0.72	73	10728	382	39
Grassland	2.22	1.32	4	13.78	7.24	4			
High Level	2.32	0.91	4	8.48	4.06	4			
Hythe	4.76	0.84	7	19.14	4.67	7			
Jasper	4.25	.05	2	19.92	1.86	2	3948	272	13
Lac La Biche	4.11	.2	18	22.88	0.92	18	1425	78	35
Manning	4.47	0.28	9	25.19	2.28	9	464	22.3	24
Peace River	6.57	1.17	3	31.9	2.05	3			
Slave Lake	3.43	0.31	21	22.75	1.27	21	2730	38	25
Swan Hills	5.59	1.55	4	17.62	6.06	4			
Wabasca	0.95	0.12	6	11.85	3.02	6	245	27.9	35
Westlock	3.91	0.93	10	14.5	3.23	11			
Whitecourt	3.64	1.42	16	17.76	4.37	17	3417	37	39

Pulp Mill Discharges									
Weldwood of Canada Ltd.	0.7	0.03	204	4.9	0.14	138	106613	415	1450
Alberta Newsprint Company	6.5	0.40	176	6.6	0.84	56	15521	92	1256
Millar Western Pulp Ltd.	2.9	0.18	213	10.6	0.61	120	12056	62	1442
Slave Lake Pulp Corp.	12.0	1.0	207	20.7	8.10	40	4692	43	1122
Alberta Pacific Forest Industries Inc.	1.1	0.06	53	2.7	0.30	52	66997	508	365
Weyerhaeuser Canada Ltd.	1.2	0.05	218	7.8	0.45	50	58633	293	1408
Daishowa-Marubeni International Ltd.	1.7	0.05	252	6.1	0.26	137	61014	324	1248

APPENDIX C. Total phosphorus (TP) and total nitrogen (TN) concentrations and loads in the Athabasca, Wapiti and Smoky rivers and the percent contributions of municipal or pulp mill effluents to the river nutrient loads.

Total phosphorus concentrations (μg/L expressed as medians for all years in Table 3.1) and loads (tonnes averaged for all years in Table 3.1) in the Athabasca, Wapiti and Smoky rivers and the percent contributions of municipal or pulp mill effluents to the river nutrient loads. (n/a is not available due to lack of discharge data.)

Site	Annual				Low Flow (December - April)				High Flow (May - November)			
	μg/L	tonnes	% contribution to load from		μg/L	tonnes	% contribution to load from		μg/L	tonnes	% contribution to load from	
			pulp mills	municipalities			pulp mills	municipalities			pulp mills	municipalities
Athabasca River at Athabasca Falls	6.0	n/a			3.0	n/a			14.0	n/a		
below Snaring River	10.0	80	0	7.7	10.0	2.8	0	90.2	11.0	77	0	4.6
u/s Hinton	19.7	n/a			9.9	n/a			34.0	n/a		
at Obed Coal Bridge	26.2	219	13.3	2.8	25.5	20	61.3	13.0	30.4	199	8.5	1.8
at Windfall Bridge	9.7	n/a			9.2	n/a			18.0	n/a		
near Fort Assiniboine	24	n/a			25.6	n/a			21.9	n/a		
near Highway 2 Bridge	30.8	n/a			23.9	n/a			45.3	n/a		
at the Town of Athabasca	24.5	1361	6.9	1.5	17.0	95	41.1	8.7	41.0	1266	4.4	0.9
0.1 km u/s of Horse R.	24.4	1866	5.1	1.3	22.7	119	32.8	8.3	71.0	1747	3.2	0.8
at Old Fort	36.8	2311	4.1	1.5	33.2	145	26.9	9.5	61.2	2166	2.6	0.9
Wapiti River near Highway 40	9.8	125			6.2	24			13.8	101		
at mouth	68.9	204	12.9	9.5	108.7	46	23.7	17.6	46.1	158	9.7	7.2
Smoky River at Watino	41.5	2442	1.1	0.9	27.0	306	3.6	3.0	65.6	2136	0.7	0.6

Total nitrogen concentrations (μg/L expressed as medians for all years combined in Table 3.1) and loads (tonnes averaged for all years in Table 3.1) in the Athabasca, Wapiti and Smoky rivers and the percent contributions of municipal or pulp mill effluents to the river nutrient loads. (n/a is not available due to lack of discharge data.)

Site	Annual				Low Flow (December - April)				High Flow (May - November)			
	μg/L	tonnes	% contribution to load from		μg/L	tonnes	% contribution to load from		μg/L	tonnes	% contribution to load from	
			pulp mills	municipalities			pulp mills	municipalities			pulp mills	municipalities
Athabasca River at Athabasca Falls	113	n/a			121	n/a			105	n/a		
below Snaring River	120	298	0.0	9.6	144	28	0.0	42.3	98	270	0.0	6.2
u/s Hinton	236	n/a			217	n/a			344	n/a		
at Obed Coal Bridge	373	2254	8.7	1.3	415	209	38.7	5.7	289	2045	5.6	0.8
at Windfall Bridge	313	n/a			313	n/a			305	n/a		
near Fort Assiniboine	353	n/a			369	n/a			193	n/a		
near Highway 2 Bridge	408	n/a			433	n/a			308	n/a		
at the Town of Athabasca	422	6816	4.6	1.4	490	1245	10.4	3.2	363	5571	3.3	1.0
0.1 km u/s of Horse R.	571	8980	3.5	1.3	531	1250	10.3	3.9	638	7730	2.4	0.9
at Old Fort	440	13670	2.3	1.8	498	1840	7.0	5.4	339	11830	1.5	1.2
Wapiti River near Highway 40	289	1018			259	204			335	814		
at mouth	747	1335	12.8	6.8	857	318	22.3	11.8	512	1017	9.9	5.2
Smoky River at Watino	480	6421	2.7	1.6	480	1127	6.3	3.8	472	5294	1.9	1.1

APPENDIX D. Total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN) and dissolved inorganic nitrogen (DIN) export coefficients for forested basins in North America.

				Export Coefficient (kg/km²/y)					
watershed (km²)	watershed location	sample date	% forest	TP	SRP	TN	DIN	citation	comments
3.34	stream 01, into L. Wabamun, AB.	1980	92	13.0		126		Mitchell, 1985.	
0.67	stream 02, into L. Wabamun, AB.	1980	92	10.0		64		Mitchell, 1985.	
2.10	stream 09, into L. Wabamun, AB.	1980	84	19.0		154		Mitchell, 1985.	
11.71	stream 12, into L. Wabamun, AB.	1980	88	5.0		29		Mitchell, 1985.	
5.75	stream 20, into L. Wabamun, AB.	1980	91	14.0		176		Mitchell, 1985.	
3.34	stream 01, into L. Wabamun, AB.	1981	92	9.0		52		Mitchell, 1985.	
0.67	stream 02, into L. Wabamun, AB.	1981	92	22.0		235		Mitchell, 1985.	
2.10	stream 09, into L. Wabamun, AB.	1981	84	12.0		66		Mitchell, 1985.	
11.71	stream 12, into L. Wabamun, AB.	1981	88	5.0		23		Mitchell, 1985.	
5.75	stream 20, into L. Wabamun, AB.	1981	91	8.0		66		Mitchell, 1985.	
161	Two Creek, AB. drains into Athabasca R.	1983	100	12.64	3.21			Munn and Prepas, 1986	
281	Sakwatamau River, AB. " "	1983	100	7.47	1.87			Munn and Prepas, 1986	
7.33	Stream D into Baptiste Lake, AB.	1976	73.7	5	3	56		Trew *et al.*, 1987	
90.5	Stream E into Baptiste Lake, AB.	1976	82.6	12	3	67		Trew *et al.*, 1987	
56.57	Stream F into Baptiste Lake, AB.	1976	98.3	12	3	81		Trew *et al.*, 1987	
3.09	Stream K into Baptiste Lake, AB.	1976	92.8	15	8	90		Trew *et al.*, 1987	ephemeral stream
89.01	Stream L into Baptiste Lake, AB.	1976	83.5	3	2	25		Trew *et al.*, 1987	
7.33	Stream D into Baptiste Lake, AB.	1977	73.7	9	4	147		Trew *et al.*, 1987	
90.5	Stream E into Baptiste Lake, AB.	1977	82.6	7	2	91		Trew *et al.*, 1987	
56.57	Stream F into Baptiste Lake, AB.	1977	98.3	15	3	240		Trew *et al.*, 1987	
3.09	Stream K into Baptiste Lake, AB.	1977	92.8	15	9	95		Trew *et al.*, 1987	ephemeral stream
89.01	Stream L into Baptiste Lake, AB.	1977	83.5	7	3	121		Trew *et al.*, 1987	
7.33	Stream D into Baptiste Lake, AB.	1978	73.7	16	9	193		Trew *et al.*, 1987	
90.5	Stream E into Baptiste Lake, AB.	1978	82.6	25	9	332		Trew *et al.*, 1987	
56.57	Stream F into Baptiste Lake, AB.	1978	98.3	25	8	385		Trew *et al.*, 1987	
3.09	Stream K into Baptiste Lake, AB.	1978	92.8	2	1	57		Trew *et al.*, 1987	ephemeral stream
89.01	Stream L into Baptiste Lake, AB.	1978	83.5	22	10	332		Trew *et al.*, 1987	
12548.7	Trent River, Ontario	1965	55-70		7			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1966	55-70		2			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1967	55-70		5			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1968	55-70		2.5			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1969	55-70		3.5			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1970	55-70		1.8			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1971	55-70		1.5			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1972	55-70		2			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1973	55-70		2			Minns and Johnson, 1979	estimated from graphs
12548.7	Trent River, Ontario	1974	55-70		1.8			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1965	55-70		7.5			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1966	55-70		5.5			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1967	55-70		8			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1968	55-70		4			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1969	55-70		5			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1970	55-70		3.5			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1971	55-70		3.4			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1972	55-70		4.5			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1973	55-70		5			Minns and Johnson, 1979	estimated from graphs
2737.2	Moira River, Ontario	1974	55-70		5			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1965	55-70		7			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1966	55-70		2			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1967	55-70		2.5			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1968	55-70		2			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1969	55-70		4.5			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1970	55-70		1.5			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1971	55-70		2			Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1972	55-70		2			Minns and Johnson, 1979	estimated from graphs

897.5	Salmon River, Ontario	1973	55-70		2.5	Minns and Johnson, 1979	estimated from graphs
897.5	Salmon River, Ontario	1974	55-70		2.6	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1965	55-70		5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1966	55-70		4.5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1967	55-70		4.5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1968	55-70		4.5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1969	55-70		4.8	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1970	55-70		3.5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1971	55-70		2.5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1972	55-70		2.5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1973	55-70		2.5	Minns and Johnson, 1979	estimated from graphs
787	Napanee River, Ontario	1974	55-70		2.5	Minns and Johnson, 1979	estimated from graphs
0.0048-0.0218	6 watersheds in Clemson Exp. Forest, S. Carolina	1976-78			0.50	VanLear *et al.*, 1985	
0.0048-0.0218	6 watersheds in Clemson Exp. Forest, S. Carolina	1980			0.40	VanLear *et al.*, 1985	
0.0048-0.0218	6 watersheds in Clemson Exp. Forest, S. Carolina	1981			0.60	VanLear *et al.*, 1985	
0.0048-0.0218	6 watersheds in Clemson Exp. Forest, S. Carolina	1982			1.70	VanLear *et al.*, 1985	
0.176	woodland near Coshton, Ohio				3.5	Taylor *et al.*, 1971	from Reckhow et.al., 1980
0.176	woodland near Coshton, Ohio				7.2	Taylor *et al.*, 1971	from Reckhow et.al., 1980
0.176	woodland near Coshton, Ohio				3.5	Taylor *et al.*, 1971	from Reckhow et.al., 1980
.121-.611	Coweeta hydrologic lab, North Carolina				2	Swank and Douglas, 1978	from Reckhow et.al., 1980
.121-.611	Coweeta hydrologic lab, North Carolina				2	Swank and Douglas, 1978	from Reckhow et.al., 1980
.121-.611	Coweeta hydrologic lab, North Carolina				2	Swank and Douglas, 1978	from Reckhow et.al., 1980
.121-.611	Coweeta hydrologic lab, North Carolina				3	Swank and Douglas, 1978	from Reckhow et.al., 1980
.121-.611	Coweeta hydrologic lab, North Carolina				2	Swank and Douglas, 1978	from Reckhow et.al., 1980
.121-.611	Coweeta hydrologic lab, North Carolina				2	Swank and Douglas, 1978	from Reckhow et.al., 1980
.121-.611	Coweeta hydrologic lab, North Carolina				3	Swank and Douglas, 1978	from Reckhow et.al., 1980
0.0281	Mississippi				4	Schreiber *et al.*, 1976	from Reckhow et.al., 1980
0.0193	Mississippi				5	Schreiber *et al.*, 1976	from Reckhow et.al., 1980
0.0239	Mississippi				4	Schreiber *et al.*, 1976	from Reckhow et.al., 1980
0.0164	Mississippi				4	Schreiber *et al.*, 1976	from Reckhow et.al., 1980
0.0149	Mississippi				5	Schreiber *et al.*, 1976	from Reckhow et.al., 1980
3.40	Inflow (B) Haliburton Lake, Ont	1971-72	100	6.3		Dillon and Kirchner, 1975	
0.40	Inflow (D) Haliburton Lake, Ont.	1971-72	100	4.6		Dillon and Kirchner, 1975	
2.4	Inflow (11) Haliburton Lake, Ont.	1971-72	100	7.2		Dillon and Kirchner, 1975	
5.0	Baker Creek, Ont.	1971-72	75	8.1		Dillon and Kirchner, 1975	
11.8	Little Boshkung Creek, Ont.	1971-72	75	9.6		Dillon and Kirchner, 1975	
5.9	N.E. Inflow Twelvemile Lake, Ont.	1971-72	80	8.3		Dillon and Kirchner, 1975	
515.0	Gull River at Boshkung Lake, Ont.	1971-72	100	3.7		Dillon and Kirchner, 1975	
4.1	N. inflow Moose Lake, Ont.	1971-72	100	7.7		Dillon and Kirchner, 1975	
14.9	Inflow (1) Moose Lake, Ont.	1971-72	100	4.8		Dillon and Kirchner, 1975	
3.9	Inflow (2) Moose Lake, Ont.	1971-72	100	3.8		Dillon and Kirchner, 1975	
157.9	Gull River at Moose Lake, Ont.	1971-72	100	2.7		Dillon and Kirchner, 1975	
6.1	N. inflow Maple Lake, Ont.	1971-72	85	16.0		Dillon and Kirchner, 1975	
8.9	Hurricane Creek, Ont.	1971-72	90	13.0		Dillon and Kirchner, 1975	
1.9	N.W. Inflow Bob Lake, Ont.	1971-72	100	14.5		Dillon and Kirchner, 1975	
5.30	E. inflw Cameron Lake, Ont.	1971-72	100	9.2		Dillon and Kirchner, 1975	
5.60	N.E. Four Mile Lake, Ont.	1971-72	100	12.2		Dillon and Kirchner, 1975	
20.7	N.W. inflow Four Mile Lake, Ont.	1971-72	100	6.7		Dillon and Kirchner, 1975	
1491.0	Burnt River at Cameron Lake, Ont.	1971-72	75	9.5		Dillon and Kirchner, 1975	
1648.0	Gull River at Cameron Lake, Ont.	1971-72	80	4.5		Dillon and Kirchner, 1975	
0.13	Watershed No. 6, Hubbard Brook, USA	1971-72	100	2.13		Bormann, *et al.*, 1974	four year mean
0.2	Stream BC1, Muskoka-Haliburton area, Ont.	1976-84		2.48		Dillon *et al*, 1991	nine year mean
5.72	Stream BE1, Muskoka-Haliburton area, Ont.	1976-84		7.56		Dillon *et al*, 1991	nine year mean
0.6	Stream CB1, Muskoka-Haliburton area, Ont.	1976-84		3.87		Dillon *et al*, 1991	nine year mean
1.26	Stream CB2, Muskoka-Haliburton area, Ont.	1976-84		12.3		Dillon *et al*, 1991	nine year mean
4.56	Stream CN1, Muskoka-Haliburton area, Ont.	1976-84		8.58		Dillon *et al*, 1991	nine year mean
0.79	Stream DE10, Muskoka-Haliburton area, Ont.	1976-84		12.45		Dillon *et al*, 1991	nine year mean
0.76	Stream DE11, Muskoka-Haliburton area, Ont.	1976-84		14.71		Dillon *et al*, 1991	nine year mean
3.0	Stream DE5, Muskoka-Haliburton area, Ont.	1976-84		28.77		Dillon *et al*, 1991	nine year mean
0.22	Stream DE6, Muskoka-Haliburton area, Ont.	1976-84		35.0		Dillon *et al*, 1991	nine year mean
0.67	Stream DE*, Muskoka-Haliburton area, Ont.	1976-84		7.22		Dillon *et al*, 1991	nine year mean
0.47	Stream DK1, Muskoka-Haliburton area, Ont.	1976-84		3.69		Dillon *et al*, 1991	nine year mean
0.48	Stream HD1, Muskoka-Haliburton area, Ont.	1976-84		9.07		Dillon *et al*, 1991	nine year mean
0.66	Stream HAL12, Muskoka-Haliburton area, Ont.	1976-84		11.24		Dillon *et al*, 1991	nine year mean
0.26	Stream HP3, Muskoka-Haliburton area, Ont.	1976-84		13.01		Dillon *et al*, 1991	nine year mean

0.2	Stream HP3A, Muskoka-Haliburton area, Ont.	1976-84		4.61				Dillon *et al*, 1991	nine year mean
1.2	Stream HP4, Muskoka-Haliburton area, Ont.	1976-84		9.2				Dillon *et al*, 1991	nine year mean
1.91	Stream HZP5, Muskoka-Haliburton area Ont.	1976-84		10.1				Dillon *et al*, 1991	nine year mean
0.1	Stream HP6, Muskoka-Haliburton area, Ont.	1976-84		8.61				Dillon *et al*, 1991	nine year mean
0.15	Stream HP6A, Muskoka-Haliburton area, Ont.	1976-84		6.22				Dillon *et al*, 1991	nine year mean
0.07	Stream JY1, Muskoka-Haliburton area, Ont.	1976-84		4.55				Dillon *et al*, 1991	nine year mean
6.66	Stream JY3, Muskoka-Haliburton area, Ont.	1976-84		9.66				Dillon *et al*, 1991	nine year mean
0.41	Stream JY4, Muskoka-Haliburton area, Ont.	1976-84		4.12				Dillon *et al*, 1991	nine year mean
4.38	Stream ME1, Muskoka-Haliburton area Ont.	1976-84		7.0				Dillon *et al*, 1991	nine year mean
0.23	Stream PC1, Muskoka-Haliburton area, Ont.	1976-84		5.42				Dillon *et al*, 1991	nine year mean
0.21	Stream PT1, Muskoka-Haliburton area, Ont.	1976-84		2.03				Dillon *et al*, 1991	nine year mean
1.34	Stream RC1, Muskoka-Haliburton area, Ont.	1976-84		6.1				Dillon *et al*, 1991	nine year mean
0.27	Stream RC2, Muskoka-Haliburton area, Ont.	1976-84		5.76				Dillon *et al*, 1991	nine year mean
0.7	Stream RC3, Muskoka-Haliburton area, Ont.	1976-84		7.9				Dillon *et al*, 1991	nine year mean
0.45	Stream RC4, Muskoka-Haliburton area, Ont.	1976-84		11.15				Dillon *et al*, 1991	nine year mean
0.79	Stream TBAY1, Muskoka-Haliburton area, Ont.	1976-84		3.96				Dillon *et al*, 1991	nine year mean
4.27	Stream TWN1, Muskoka-Haliburton area Ont.	1976-84		8.21				Dillon *et al*, 1991	nine year mean
1.72	Stream TWS1, Muskoka-Haliburton area Ont.	1976-84		8.27				Dillon *et al*, 1991	nine year mean
9.6	Kearney W, Ontario			3.9				Kirchner, 1975	
3.5	Kearney E, Ontario			2.7				Kirchner, 1975	
3.3	Costello, Ontario			4.1				Kirchner, 1975	
1.6	Brewer, Ontario			8.5				Kirchner, 1975	
3.1	Haliburton A, Ontario			4.7				Kirchner, 1975	
13.0	Haliburton C, Ontario			7.5				Kirchner, 1975	
0.26	Haliburton D, Ontario			5.2				Kirchner, 1975	
5.8	Haliburton 1, Ontario			5.0				Kirchner, 1975	
4.1	Haliburton 4, Ontario			3.7				Kirchner, 1975	
13.0	Halibuton 7, Ontario			2.5				Kirchner, 1975	
2.9	Halibuton 8, Ontario			6.0				Kirchner, 1975	
4.9	Oblong, Ontario			5.2				Kirchner, 1975	
15.0	Moose, Ontario			4.4				Kirchner, 1975	
1.1	Eagle, Ontario			4.1				Kirchner, 1975	
18.6	Bob, Ontario			7.0				Kirchner, 1975	
73.3	Percy, Ontario			3.0				Kirchner, 1975	
85.6	Buckslides, Ontario			3.5				Kirchner, 1975	
254.0	Kennisis, Ontario			2.5				Kirchner, 1975	
14878.0	Arctic Red River, NWT	1971-74		127.1				Brunskill *et al.*, 1975	
245454.0	Liard River, NWT	1971-74		34.1				Brunskill *et al.*, 1975	
67273.0	Peel River, NWT	1971-74		34.1				Brunskill *et al.*, 1975	
15278.0	South Nahanni River, ,Virginia Falls, NWT	1971-74		22.3				Brunskill *et al.*, 1975	
392.0	Caribou Bar Creek, Yukon	1971-74		8.68				Brunskill *et al.*, 1975	
145000.0	Great Bear River, NWT	1971-74		6.2				Brunskill *et al.*, 1975	
500.0	Harris River, NWT	1971-74		0.62				Brunskill *et al.*, 1975	
2143.0	Martin River, NWT	1971-74		2.17				Brunskill *et al.*, 1975	
22308.0	Willowlake River, NWT	1971-74		4.03				Brunskill *et al.*, 1975	
0.03	Coffeeville, Mississippi	1974		9.4	2.9			Duffy *et al.*, 1978	
0.02	Coffeeville, Mississippi	1974		11				Duffy *et al.*, 1978	
0.02	Coffeeville, Mississippi	1974		9.7				Duffy *et al.*, 1978	
0.02	Coffeeville, Mississippi	1974		8.3				Duffy *et al.*, 1978	
0.01	Coffeeville, Mississippi	1974		5.5				Duffy *et al.*, 1978	
0.00	Lake Minnetonka Watershed, Minnesota			6				Singer and Rust, 1975	
0.18	Coshocton, Ohio	1967		3.5		137		Taylor et al., 1971	
0.18	Coshocton, Ohio	1968		7.2		316		Taylor *et al.*, 1971	
0.18	Coshocton, Ohio	1969		3.5		282		Taylor *et al.*, 1971	
0.13	Hubbard Creek No. 6, New Hampshire	1968-69		0.9				Hobbie and Likens, 1973	
64.95	Watershed P-10, Woodlands, Texas	1971-74		21				Bedient *et al.*, 1978	
1546	Bad River, Wisconsin	1975-77	89	12.7		393		Clesceri *et al.*, 1986	
360	Popple River, Wisconsin	1973,75-82	90	8.6				Clesceri *et al.*, 1986	
57.7	Butternut River, Wisconsin	1973	82	12.4	5.7	350	77	Clesceri *et al.*, 1986	
1.7	central Canada			5.07		102		Schindler *et al.*, 1976	
1.7	central Canada			6.59		106		Schindler *et al.*, 1976	
1.7	central Canada			5.07		102		Schindler *et al.*, 1976	
1.7	central Canada			4.18		96.6		Schindler *et al.*, 1976	
0.63	central Canada			5.57		102		Schindler *et al.*, 1976	
0.63	central Canada			7.18		136		Schindler *et al.*, 1976	

0.63	central Canada			2.52		70.3		Schindler *et al.*, 1976	
0.63	central Canada			1.86		60.5		Schindler *et al.*, 1976	
0.1	central Canada			10.7				Schindler *et al.*, 1976	
0.1	central Canada			9.68				Schindler *et al.*, 1976	
0.1	central Canada			1.79				Schindler *et al.*, 1976	
3.42	central Canada			5.22		102		Schindler *et al.*, 1976	
3.42	central Canada			6.91		116		Schindler *et al.*, 1976	
3.42	central Canada			4.63		68.3		Schindler *et al.*, 1976	
3.42	central Canada			3.49		90.4		Schindler *et al.*, 1976	
65.0	central Canada			9				Ryding and Forsberg, 1979	
1.26	Bear Brook, Hubbard Brook Experimental Forest, USA	1969		10.6				Meyer and Likens, 1979	from Reckhow et.al., 1980
21.5	Watershed No. 2, North Minnesota			11.0				Cooper, 1969	from Uttomark et al., 1974
28.5	Watershed No. 3, North Minnesota			18.3				Cooper, 1969	from Uttomark et al., 1974
9.58	Watershed No. 4, North Minnesota			8.4				Cooper, 1969	from Uttomark et al., 1974
130.0	Watershed No. 6, North Minnesota			13.5				Cooper, 1969	from Uttomark et al., 1974
	forested watershed in the Potomac River basin, USA		88	1				Jaworski and Helting , 1970	from Uttomark et al., 1974
1.25	Clear Lake Watershed Haliburton County, Ont.			9				Schlinder and Nighswander, 1970	
	Northwest Ontario			6		237		Nicholson, 1977	from Reckhow, et al., 1980
	Northwest Ontario			3.6		1384		Nicholson, 1977	from Reckhow, et al., 1980
0.1	Marcell Experimental Forest, Minnesota			12.4		226		Verry, 1979	from Reckhow, et al., 1980
0.1	Marcell Experimental Forest, Minnesota			17.9		237		Verry, 1979	from Reckhow, et al., 1980
0.1	Marcell Experimental Forest, Minnesota			15.7		174		Verry, 1979	from Reckhow, et al., 1980
0.06	Marcell Experimental Forest, Minnesota			19	5	246		Timmons *et al.*, 1977	from Reckhow, et al., 1980
0.06	Marcell Experimental Forest, Minnesota			38	20	329		Timmons *et al.*, 1977	from Reckhow, et al., 1980
0.06	Marcell Experimental Forest, Minnesota			28	16	192		Timmons *et al.*, 1977	from Reckhow, et al., 1980
0.16	Watershed #6 Hubbard Brook Experimental Forest, New Hampshire			1.9		401		Likens *et al.*, 1977	from Reckhow, et al., 1980
0.98	Walker branch Watershed, Oak Ridge, Tennessee			1		220		Henderson *et al.*, 1978	from Reckhow, et al., 1980
0.98	Walker branch Watershed, Oak Ridge, Tennessee			2		170		Henderson *et al.*, 1978	from Reckhow, et al., 1980
0.98	Walker branch Watershed, Oak Ridge, Tennessee			3				Henderson *et al.*, 1978	from Reckhow, et al., 1980
0.98	Walker branch Watershed, Oak Ridge, Tennessee			3				Henderson *et al.*, 1978	from Reckhow, et al., 1980
0.34	Fenrow Experimental Forest, Parsons, West Virginia			18				Aubertin and Patric, 1974	from Reckhow, et al., 1980
0.34	Fenrow Experimental Forest, Parsons, West Virginia			14				Aubertin and Patric, 1974	from Reckhow, et al., 1980
0.34	Fenrow Experimental Forest, Parsons, West Virginia			8				Aubertin and Patric, 1974	from Reckhow, et al., 1980
0.4	Eatonia, Georgia			27.5				Krebs and Golley, 1977	from Reckhow, et al., 1980
	Rhode River Watershed, Maryland			20		150		Correll *et al.*, 1978	from Reckhow, et al., 1980
	Stetson Stream, Maine			3.5				Mackenthun et al., 1968	from Dillon and Kirchner, 1975
	E. Sebasticook River, Maine			5.6				Mackenthun et al., 1968	from Dillon and Kirchner, 1975
	Mulligan Stream, Maine			0.7				Mackenthun et al., 1968	from Dillon and Kirchner, 1975
5.44	Alabama, Holt Lock and Dam, 0105B1		75			640.7	381.3	Omnerick, 1977	
3.11	Alabama, Holt Lock and Dam, 0105C1		75			662.4	390.2	Omnerick, 1977	
29.86	Alabama, Holt Lock and Dam, 0105D1		75			442.7	250.7	Omnerick, 1977	
43.36	Alabama, Martin Lake, 0107H1		75			159.9	34.7	Omnerick, 1977	
25.11	Arizona, Fools Hollow Lake, 0402C1	1974	75	0.3	0.1	4.7	0.3	Omnerick, 1977	
70.73	Arizona, Rainbow Lake, 04091C	1974	75	14.8	7.5	240.7	13.3	Omnerick, 1977	
30.83	Arkansas, Blue Mountain Lake, 0503E1	1974	75	7.9	3.2	217.5	19.4	Omnerick, 1977	
150.28	Arkansas, Blue Mountain Lake, 0503F1	1974	75	7.1	3	171.2	26.4	Omnerick, 1977	
41.57	Arkansas, Bull Shoals Reservoir, 0504C1	1974	75	2.6	1.7	84.8	34.9	Omnerick, 1977	
19.9	Arkansas, De Gray Reservoir, 0507D1	1974	75	5.4	2.5	61.9	9.1	Omnerick, 1977	
23.27	Arkansas, Norfolk Lake, 0513D1	1974	75	3.9	2.6	210.7	108.2	Omnerick, 1977	
38.79	California, Iron Gate Reservoir, 0611C1	1974	75	37.3	27.1	783.1	67.8	Omnerick, 1977	
8.91	California, Lake Pillsbury, 0619C1	1974	75	39.6	18.3	643	38.8	Omnerick, 1977	
32.68	California, Lake Pillsbury, 0619D1	1974	75	45.6	13.5	488.4	20.9	Omnerick, 1977	
157.64	California, Lake Shasta, 0621F1	1974	75	24	13.9	1105.8	59.3	Omnerick, 1977	
25.03	California, Lake Shasta, 0621J1	1974	75	19.8	13.2	839.5	73.3	Omnerick, 1977	
16.38	California, Lower Utah Reservoir, 0618G1	1974	75	2.1	0.7	150.7	79.3	Omnerick, 1977	
46.54	Georgia, Allatoona Reservoir, 1301F1		75			178.3	18.2	Omnerick, 1977	
16.96	Georgia, Blue Ridge Lake, 1316E1		75			425.8	39	Omnerick, 1977	
16.14	Georgia, Burton Lake, 1318B1		75			450.9	85.5	Omnerick, 1977	
20.33	Georgia, Burton Lake, 1318C1		75			488.7	69.2	Omnerick, 1977	
17.25	Georgia, Burton Lake, 1318D1		75			366.8	55.8	Omnerick, 1977	
14.71	Georgia, Burton Lake, 1318E1		75			376.2	87.4	Omnerick, 1977	
153.99	Idaho, Cour D'alene lake, 1603C1	1974	75	5.5	3.3	175.7	23.3	Omnerick, 1977	
37.69	Idaho, Cour D'alene lake, 1603K1	1974	75	5.6	3.4	77.2	10	Omnerick, 1977	
17.06	Idaho, Dworshak Reservoir, 1604C1	1974	75	28	14.5	522.5	52.4	Omnerick, 1977	

79.64	Idaho, Dworshak Reservoir, 1604J1	1974	75	10.6	4.8	451.3	55.8	Omnerick, 1977
72.79	Idaho, Haden Lake, 1606A2	1974	75	6.3	3.2	188.8	23.3	Omnerick, 1977
12.26	Idaho, Haden Lake, 1606B1	1974	75	7.4	4.7	423	16	Omnerick, 1977
21.59	Idaho, Haden Lake, 1606C1	1974	75	11	4.4	298.5	11.8	Omnerick, 1977
38.2	Idaho, Island Park Reservoir, 1607B1	1974	75	17.6	12	252.8	21.9	Omnerick, 1977
7.35	Idaho, Twin Lakes, 1612B1	1974	75	18.7	5.1	288.6	103.3	Omnerick, 1977
6.65	Idaho, Twin Lakes, 1612C1	1974	75	11.6	7.5	322.7	19.6	Omnerick, 1977
46.36	Kentucky, Lake Cumberland, 2101S1		75			254.5	43.2	Omnerick, 1977
18.14	Louisiana, Anacoca Lake, 2201B1	1974	75	9.7	4	304.7	31.8	Omnerick, 1977
8.22	Louisiana, Black Bayou, 2204F1	1974	75	13.3	6.1	200.9	26	Omnerick, 1977
25.61	Louisiana, Cross Lake, 2210E1	1974	75	15	6.9	177.8	29	Omnerick, 1977
18.75	Maine, Moosehead Lake, 2309K1		75			201.1	69.3	Omnerick, 1977
39.08	Maine, Rangely Lake, 2310B1		75			331.4	96.6	Omnerick, 1977
7.2	Maryland, Deep Creek Lake, 2402C1		75			565.6	222.1	Omnerick, 1977
11.38	Missouri, Clearwater Reservoir, 2901D1	1974	75	2.8	1.4	252.1	18.6	Omnerick, 1977
28.73	Missouri, Lake Wappapello, 2906F1	1974	75	4.6	2.3	355	47.6	Omnerick, 1977
16.66	Montana, Flathead Lake, 3003H1	1974	75	2.4	2.4	72.5	11.8	Omnerick, 1977
7.76	Montana, Georgetown Lake, 3004D1	1974	75	11.4	1.3	97	8.1	Omnerick, 1977
84.83	Montana, Koocanusa Reservoir, 3006F1	1974	75	8	3.3	265.6	20.1	Omnerick, 1977
39.77	Montana, Koocanusa Reservoir, 3006J1	1974	75	3.1	1.9	79.1	7.3	Omnerick, 1977
24.82	Montana, Koocanusa Reservoir, 3006K1	1974	75	7	4	124.4	10.4	Omnerick, 1977
8.49	Montana, Swan Lake, 3011C1	1974	75	12.8	7.7	663.5	23.8	Omnerick, 1977
7.3	Montana, Swan Lake, 3011E1	1974	75	8.5	4.3	965.9	184.7	Omnerick, 1977
18.36	New Hampshire, Lake Winnipesaukee, 3303K1		75			352.1	196.7	Omnerick, 1977
40.51	New Hampshire, Lake Winnipesaukee, 3303L1		75			408.1	103.8	Omnerick, 1977
23	New Hampshire, Lake Winnipesaukee, 3303U1		75			126.1	19	Omnerick, 1977
8.96	New Hampshire, Lake Winnipesaukee, 3303V1		75			508.7	75.6	Omnerick, 1977
7.56	New Hampshire, Lake Winnipesaukee, 3303X1		75			227.6	49.8	Omnerick, 1977
9.84	New Hampshire, Lake Winnipesaukee, 3303Y1		75			184.1	66	Omnerick, 1977
19.49	Nevada, Lake Tahoe, 3205N1	1974	75	20.6	12.1	548.3	42.4	Omnerick, 1977
19.98	Nevada, Washoe Lake, 32081E	1974	75	6.5	3.8	84.3	8.1	Omnerick, 1977
27.16	New Mexico, Eagle Nest Lake, 3504C1	1974	75	6.6	2	104.7	11.1	Omnerick, 1977
10.93	New York, Allegheny Reservoir, 3641H1		75			1084	522.5	Omnerick, 1977
53.51	New York, Allegheny Reservoir, 3641J1		75			720.4	309.1	Omnerick, 1977
30.23	New York, Allegheny Reservoir, 3641K1		75			559.2	204	Omnerick, 1977
51.67	New York, Allegheny Reservoir, 3641L1		75			454.8	222.5	Omnerick, 1977
55.4	New York, Allegheny Reservoir, 3641M1		75			372.3	185	Omnerick, 1977
115.41	New York, Allegheny Reservoir, 3641N1		75			632.5	185.3	Omnerick, 1977
11.29	New York, Cannonsville Reservoir, 3605B1		75			246	90.5	Omnerick, 1977
3.11	New York, Cannonsville Reservoir, 3605F1		75			485.8	228.7	Omnerick, 1977
4.92	New York, Carry Falls Reservoir, 3606B1		75			671.7	149.1	Omnerick, 1977
1.27	New York, Cassadaga Lake, 3607C1		75			394.5	226.2	Omnerick, 1977
1.71	New York, Lower St. Regis, 3640A1		75			439	173.3	Omnerick, 1977
21.57	New York, Schroon Lake, 3634D2		75			564.8	79.9	Omnerick, 1977
5.7	New York, Schroon Lake, 3634E1		75			427.8	124.3	Omnerick, 1977
5.98	New York, Schroon Lake, 3634F1		75			436.3	83.4	Omnerick, 1977
61.77	New York, Schroon Lake, 3634G1		75			682.6	75.5	Omnerick, 1977
29.03	North Carolina, Fontana Lake, 3704E1		75			205.7	84.2	Omnerick, 1977
110.62	North Carolina, Santeetlah Lake, 3716D1		75			489.8	105.9	Omnerick, 1977
35.66	North Carolina, Santeetlah Lake, 3716E1		75			474.3	112.2	Omnerick, 1977
72.88	North Carolina, Santeetlah Lake, 3716F1		75			511.3	146.2	Omnerick, 1977
30.63	Oregon, Hills Creek Reservoir, 4104B1	1974	75	40.1	29.3	225	24.5	Omnerick, 1977
23.99	Oregon, Hills Creek Reservoir, 4104C1	1974	75	48.9	41.1	268	37.2	Omnerick, 1977
137.36	Oregon, Hills Creek Reservoir, 4104D1	1974	75	32.7	25.7	219.7	38.6	Omnerick, 1977
8.73	Pennsylvania, Indian Lake, 4223C1		75			629.3	159.5	Omnerick, 1977
19.3	Pennsylvania, Indian Lake, 4223D1		75			581.7	276.4	Omnerick, 1977
10.08	Pennsylvania, Lake Wallenpaupack, 4229C1		75			590.7	97.3	Omnerick, 1977
77.78	South Carolina, Keowee lake, 4513E1		75			211.7	44.7	Omnerick, 1977
30.64	South Carolina, Keowee lake, 4513G1		75			488.4	76.2	Omnerick, 1977
203.71	South Dakota, Deerfield Lake, 4610A2	1974	75	1.3	0.5	25.7	4.9	Omnerick, 1977
70	South Dakota, Deerfield Lake, 4610A3	1974	75	1.1	0.4	22.7	7.1	Omnerick, 1977
16.79	South Dakota, Deerfield Lake, 4610B1	1974	75	2.6	1.4	37.3	2.5	Omnerick, 1977
26.08	South Dakota, Pactola Reservoir, 4620C1	1974	75	1.9	0.5	38.5	6.7	Omnerick, 1977
16.12	South Dakota, Pactola Reservoir, 4620D1	1974	75	1	0.5	37.1	11.9	Omnerick, 1977
59.03	Tennessee, Nickajack reservoir, 4717E1		75			367.3	89.2	Omnerick, 1977

10.49	Tennessee, Nickajack reservoir, 4717M1		75			893.4	201	Omnerick, 1977
4.69	Tennessee, Nickajack reservoir, 4717N1		75			326.5	69.8	Omnerick, 1977
3.39	Tennessee, Nickajack reservoir, 4717P1		75			412.1	49.9	Omnerick, 1977
3.89	Tennessee, Nickajack reservoir, 4717Q1		75			334.5	62.9	Omnerick, 1977
2.38	Tennessee, Nickajack reservoir, 4717R1		75			295.6	51.4	Omnerick, 1977
42.37	Tennessee, Nickajack reservoir, 4717T1		75			545.5	82.9	Omnerick, 1977
57.94	Texas, Lake of the Pines, 4818P1	1974	75	12.3	4.1	183.3	43.9	Omnerick, 1977
51.96	Texas, Livingston Lake, 4820B1	1974	75	3.3	2.2	82.8	10.6	Omnerick, 1977
18.73	Texas, Sam Rayburn Reservoir, 4827H1	1974	75	1.6	0.7	47.1	8.7	Omnerick, 1977
11.59	Texas, Sam Rayburn Reservoir, 4827P1	1974	75	10.1	3.6	127.7	10.8	Omnerick, 1977
48.02	Virginia, Claytor Lake, 5103B1		75			118.8	35.9	Omnerick, 1977
7.25	Virginia, John W Flannagan Reservoir, 5105F1		75			327.7	59.2	Omnerick, 1977
108.3	Washington, Chelan Lake, 5303E1	1974	75	5.8	4.5	114.1	42.3	Omnerick, 1977
91.01	Washington, Keechelus Lake, 53061H	1974	75	22.7	20.4	263.3	56.7	Omnerick, 1977
10.44	Washington, Keechelus Lake, 5306D1	1974	75	15.9	13.6	600.4	111	Omnerick, 1977
20.5	Washington, Ozette Lake, 5310D1	1974	75	112.6	52.5	2117	525.5	Omnerick, 1977
58.3	Wyoming, Flaming Gorge Reservoir, 5605B1	1974	75	5	1.3	130.9	9.4	Omnerick, 1977
28.63	Arkansas, Blue Mountain Lake, 0503D1	1974	90	9.8	3.3	306.3	19.3	Omnerick, 1977
5.23	Arkansas, De Gray Reservoir, 0507B1	1974	90	10.1	3.9	92.1	20.7	Omnerick, 1977
51.7	Arkansas, Nimrod Lake, 0512B1	1974	90	6.7	3.3	194.6	24.8	Omnerick, 1977
25.45	Arkansas, Nimrod Lake, 0512C1	1974	90	7.6	3.1	272.6	21.8	Omnerick, 1977
53.85	Arkansas, Nimrod Lake, 0512E1	1974	90	6.8	3.4	217.6	20.1	Omnerick, 1977
41.34	Arkansas, Nimrod Lake, 0512F1	1974	90	10.7	3.8	160.2	48.3	Omnerick, 1977
22.59	Arkansas, Quachita Lake, 0514B1	1974	90	10	6.1	95.2	13.4	Omnerick, 1977
27.34	Arkansas, Quachita Lake, 0514C1	1974	90	7	5.1	134.1	16.3	Omnerick, 1977
10.31	Arkansas, Quachita Lake, 0514H1	1974	90	6.8	4	231	20.3	Omnerick, 1977
225.88	California, Lake Pillsbury, 0619B1	1974	90	17.1	9.2	351.9	38.2	Omnerick, 1977
33.17	California, Lake Pillsbury, 0619E1	1974	90	26.4	11.7	766	22	Omnerick, 1977
35.19	California, Lake Shasta, 0621C1	1974	90	15.3	8.4	751.5	29.8	Omnerick, 1977
28.45	California, Lake Shasta, 0621E1	1974	90	19.8	9.9	1497.9	87.8	Omnerick, 1977
13.68	California, Lake Shasta, 0621H1	1974	90	24.1	17.6	1255.2	60.4	Omnerick, 1977
3.35	Colorado, Shadow Mountain Reservoir, 0813F1	1974	90	5	2.4	118.9	15.8	Omnerick, 1977
26.38	Idaho, Dworshak Reservoir, 1604D1	1974	90	27.9	17.3	461.9	30.8	Omnerick, 1977
24.87	Idaho, Dworshak Reservoir, 1604E1	1974	90	23.1	8.7	378.2	27.9	Omnerick, 1977
161.5	Idaho, Dworshak Reservoir, 1604F1	1974	90	34.4	28.7	289.9	27.7	Omnerick, 1977
332.76	Idaho, Dworshak Reservoir, 1604G1	1974	90	17.7	13.6	434.7	34.4	Omnerick, 1977
37.94	Idaho, Twin Lakes, 1612D1	1974	90	15.2	7.6	282.9	28.9	Omnerick, 1977
15.01	Montana, Flathead Lake, 3003E1	1974	90	0.3	0.2	13	1.5	Omnerick, 1977
5.36	Montana, Flathead Lake, 3003J1	1974	90	3.5	2.9	71.9	7.7	Omnerick, 1977
61.98	Montana, Koocanusa Reservoir, 3006B1	1974	90	3.8	1.6	99.2	9.3	Omnerick, 1977
41.71	Montana, Koocanusa Reservoir, 3006G1	1974	90	14.5	7.5	343.5	18.7	Omnerick, 1977
37.29	Montana, Koocanusa Reservoir, 3006H1	1974	90	8.4	4.7	157.4	12.2	Omnerick, 1977
44.61	Montana, Koocanusa Reservoir, 3006L1	1974	90	2.7	2.3	59.1	5.5	Omnerick, 1977
43.07	Montana, Lower Whitefish, 3016C1	1974	90	11.5	5.4	482.3	62	Omnerick, 1977
31.79	Montana, Mary Ronan Lake, 3007B1	1974	90	2.5	0.9	22.4	1.8	Omnerick, 1977
5.7	Montana, Mary Ronan Lake, 3007C1	1974	90	6.4	2.3	127.8	7.1	Omnerick, 1977
0.95	Montana, McDonald Lake, 3008D1	1974	90	5	2	239.7	45.1	Omnerick, 1977
19.41	Montana, Swan Lake, 3011D1	1974	90	9.3	6.2	451	72.1	Omnerick, 1977
12	Montana, Swan Lake, 3011F1	1974	90	11.3	7.5	609.7	87.5	Omnerick, 1977
9.8	Nevada, Lake Tahoe, 32051T	1974	90	5.5	2.4	69.7	10.7	Omnerick, 1977
6.9	Nevada, Lake Tahoe, 32051U	1974	90	9.9	6.2	92.2	6.4	Omnerick, 1977
3.99	Nevada, Lake Tahoe, 3205C2	1974	90	9.2	5.5	364.3	20.3	Omnerick, 1977
19.22	Oregon, Suttle Lake, 41071C	1974	90	8.8	4.4	1297.6	30.9	Omnerick, 1977
40.79	Oregon, Suttle Lake, 41071D	1974	90	8.2	4.1	311.7	16.4	Omnerick, 1977
23.09	South Dakota, Pactola Reservoir, 4620E1	1974	90	1.8	1.2	42.5	9.6	Omnerick, 1977
11.29	Texas, Houston Lake, 4817N1	1974	90	2.8	1.3	76.7	17	Omnerick, 1977
13.6	Texas, Houston Lake, 4817P1	1974	90	8.3	2	146.5	19.2	Omnerick, 1977
68.9	Texas, Sam Rayburn Reservoir, 4827G1	1974	90	2.8	0.9	51.3	6.6	Omnerick, 1977
13.57	Texas, Sam Rayburn Reservoir, 4827J1	1974	90	1.3	0.7	46.5	6.1	Omnerick, 1977
7.47	Texas, Sam Rayburn Reservoir, 4827K1	1974	90	2.2	1.2	78.1	8.4	Omnerick, 1977
10.81	Texas, Sam Rayburn Reservoir, 4827L1	1974	90	1.1	0.7	49.4	4.9	Omnerick, 1977
15.58	Washington, Chelan Lake, 5303D1	1974	90	4	3	50.2	17.2	Omnerick, 1977
9.78	Washington, Whatcom Lake, 5312B1	1974	90	18.4	6.8	763.9	583.3	Omnerick, 1977
5.44	Alabama, Holt Lock and Dam, 0105B1	1974	>75	10.9	3.6			Omnerick, 1976
3.11	Alabama, Holt Lock and Dam, 0105C1	1974	>75	10.1	4			Omnerick, 1976

29.86	Alabama, Holt Lock and Dam, 0105D1	1972-73	>75	5.9	3	Omnerick, 1976
43.36	Alabama, Martin Lake, 0107H1	1972-73	>75	10.4	3.9	Omnerick, 1976
46.54	Georgia, Allatoona Reservoir, 1301F1	1972-73	>75	10.7	2.7	Omnerick, 1976
16.96	Georgia, Blue Ridge Lake, 1316E1	1972-73	>75	9.1	6.3	Omnerick, 1976
16.14	Georgia, Burton Lake, 1318B1	1972-73	>75	8.5	5.3	Omnerick, 1976
20.33	Georgia, Burton Lake, 1318C1	1972-73	>75	15.7	10.5	Omnerick, 1976
17.25	Georgia, Burton Lake, 1318D1	1972-73	>75	9.7	5.4	Omnerick, 1976
14.71	Georgia, Burton Lake, 1318E1	1972-73	>75	8.5	5.3	Omnerick, 1976
46.36	Kentucky, Lake Cumberland, 2101S1	1972-73	>75	3.8	2.9	Omnerick, 1976
18.75	Maine, Moosehead Lake, 2309K1	1972-73	>75	5	3.7	Omnerick, 1976
39.08	Maine, Rangely Lake, 2310B1	1972-73	>75	5.6	2.8	Omnerick, 1976
7.2	Maryland, Deep Creek Lake, 2402C1	1972-73	>75	10.4	5.2	Omnerick, 1976
18.36	New Hampshire, Lake Winnipesaukee, 3303K1	1972-73	>75	9	3.6	Omnerick, 1976
40.51	New Hampshire, Lake Winnipesaukee, 3303L1	1972-73	>75	10.9	6	Omnerick, 1976
23	New Hampshire, Lake Winnipesaukee, 3303U1	1972-73	>75	3.9	1.4	Omnerick, 1976
8.96	New Hampshire, Lake Winnipesaukee, 3303V1	1972-73	>75	11.9	4.2	Omnerick, 1976
7.56	New Hampshire, Lake Winnipesaukee, 3303X1	1972-73	>75	11.3	4	Omnerick, 1976
9.84	New Hampshire, Lake Winnipesaukee, 3303Y1	1972-73	>75	12.1	3.6	Omnerick, 1976
10.93	New York, Allegheny Reservoir, 3641H1	1972-73	>75	10	5	Omnerick, 1976
53.51	New York, Allegheny Reservoir, 3641J1	1972-73	>75	13.8	5.5	Omnerick, 1976
30.23	New York, Allegheny Reservoir, 3641K1	1972-73	>75	4.7	2.8	Omnerick, 1976
51.67	New York, Allegheny Reservoir, 3641L1	1972-73	>75	4.3	2.4	Omnerick, 1976
55.4	New York, Allegheny Reservoir, 3641M1	1972-73	>75	3.3	1.7	Omnerick, 1976
115.41	New York, Allegheny Reservoir, 3641N1	1972-73	>75	7.6	2.7	Omnerick, 1976
11.29	New York, Cannonsville Reservoir, 3605B1	1972-73	>75	8	4.5	Omnerick, 1976
3.11	New York, Cannonsville Reservoir, 3605F1	1972-73	>75	8.5	4.2	Omnerick, 1976
4.92	New York, Carry Falls Reservoir, 3606B1	1972-73	>75	10.3	3.4	Omnerick, 1976
1.27	New York, Cassadaga Lake, 3607C1	1972-73	>75	4.9	2.5	Omnerick, 1976
1.71	New York, Lower St. Regis, 3640A1	1972-73	>75	7.2	3.9	Omnerick, 1976
21.57	New York, Schroon Lake, 3634D2	1972-73	>75	7.6	3.1	Omnerick, 1976
5.7	New York, Schroon Lake, 3634E1	1972-73	>75	5.9	3	Omnerick, 1976
5.98	New York, Schroon Lake, 3634F1	1972-73	>75	5.2	2.6	Omnerick, 1976
61.77	New York, Schroon Lake, 3634G1	1972-73	>75	6.9	2.6	Omnerick, 1976
29.03	North Carolina, Fontana Lake, 3704E1	1972-73	>75	10.5	4.9	Omnerick, 1976
110.62	North Carolina, Santeetlah Lake, 3716D1	1972-73	>75	14	8.9	Omnerick, 1976
35.66	North Carolina, Santeetlah Lake, 3716E1	1972-73	>75	10.1	5.1	Omnerick, 1976
72.88	North Carolina, Santeetlah Lake, 3716F1	1972-73	>75	5	4.1	Omnerick, 1976
8.73	Pennsylvania, Indian Lake, 4223C1	1972-73	>75	5.2	2.6	Omnerick, 1976
19.3	Pennsylvania, Indian Lake, 4223D1	1972-73	>75	7.2	2	Omnerick, 1976
10.08	Pennsylvania, Lake Wallenpaupack, 4229C1	1972-73	>75	10.6	4.2	Omnerick, 1976
77.78	South Carolina, Keowee lake, 4513E1	1972-73	>75	18.5	5.4	Omnerick, 1976
30.64	South Carolina, Keowee lake, 4513G1	1972-73	>75	14.8	4.7	Omnerick, 1976
59.03	Tennessee, Nickajack reservoir, 4717E1	1972-73	>75	7.2	4	Omnerick, 1976
10.49	Tennessee, Nickajack reservoir, 4717M1	1972-73	>75	5.6	5.6	Omnerick, 1976
4.69	Tennessee, Nickajack reservoir, 4717N1	1972-73	>75	4.8	4	Omnerick, 1976
3.39	Tennessee, Nickajack reservoir, 4717P1	1972-73	>75	5	4.2	Omnerick, 1976
3.89	Tennessee, Nickajack reservoir, 4717Q1	1972-73	>75	4.8	4	Omnerick, 1976
2.38	Tennessee, Nickajack reservoir, 4717R1	1972-73	>75	4	4	Omnerick, 1976
42.37	Tennessee, Nickajack reservoir, 4717T1	1972-73	>75	6	5	Omnerick, 1976
48.02	Virginia, Claytor Lake, 5103B1	1972-73	>75	6	1.9	Omnerick, 1976
7.25	Virginia, John W Flannagan Reservoir, 5105F1	1972-73	>75	8.6	3.5	Omnerick, 1976

APPENDIX E. Total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN) and dissolved inorganic nitrogen (DIN) export coefficients for areas with > 50% Crop Land for North America.

				Export Coefficient (kg/km^2/y)					
watershed area (km^2)	description	sampling date	% crop land	TP	SRP	TN	DIN	citation	comments
89.34	Stream A, into Baptiste Lake, Alberta	1976	85.3	3	2	22		Trew *et al.*, 1987	
0.839	Stream B, into Baptiste Lake, Alberta	1976	93	8	7	32		Trew *et al.*, 1987	
2.837	Stream C, into Baptiste Lake, Alberta	1976	60	17	9	46		Trew *et al.*, 1987	
0.705	Stream M, into Baptiste Lake, Alberta	1976	99	10	7	35		Trew *et al.*, 1987	
7.036	Stream N, into Baptiste Lake, Alberta	1976	84.3	38	22	67		Trew *et al.*, 1987	
89.34	Stream A, into Baptiste Lake, Alberta	1977	85.3	36	12	256		Trew *et al.*, 1987	
2.837	Stream C, into Baptiste Lake, Alberta	1977	60	41	22	227		Trew *et al.*, 1987	
0.705	Stream M, into Baptiste Lake, Alberta	1977	99	36	26	167		Trew *et al.*, 1987	
7.036	Stream N, into Baptiste Lake, Alberta	1977	84.3	25	11	177		Trew *et al.*, 1987	
89.34	Stream A, into Baptiste Lake, Alberta	1977	85.3	26	18	210		Trew *et al.*, 1987	
0.839	Stream B, into Baptiste Lake, Alberta	1978	93	51	39	199		Trew *et al.*, 1987	
2.837	Stream C, into Baptiste Lake, Alberta	1978	60	25	16	235		Trew *et al.*, 1987	
0.705	Stream M, into Baptiste Lake, Alberta	1978	99	35	21	250		Trew *et al.*, 1987	
7.036	Stream N, into Baptiste Lake, Alberta	1978	84.3	37	25	218		Trew *et al.*, 1987	
5.57	stream 13, into Lake Wabamun, Alta.	1980	72	63		256		Mitchell, 1985	
46.88	stream 22, into Lake Wabamun, Alta.	1980	60	12		92		Mitchell, 1985	
10.49	stream 23, into Lake Wabamun, Alta.	1980	63	36		464		Mitchell, 1985	
3.99	stream 26, into Lake Wabamun, Alta.	1980	60	6		121		Mitchell, 1985	
2.06	stream 30, into Lake Wabamun, Alta.	1980	58	6		26		Mitchell, 1985	
1.8	stream 31, into Lake Wabamun, Alta.	1980	56	6		43		Mitchell, 1985	
5.57	stream 13, into Lake Wabamun, Alta.	1981	72	34		177		Mitchell, 1985	
46.88	stream 22, into Lake Wabamun, Alta.	1981	60	12		79		Mitchell, 1985	
10.49	stream 23, into Lake Wabamun, Alta.	1981	63	8		97		Mitchell, 1985	
3.99	stream 26, into Lake Wabamun, Alta.	1981	60	9		85		Mitchell, 1985	
2.06	stream 30, into Lake Wabamun, Alta.	1981	58	12		54		Mitchell, 1985	
1.8	stream 31, into Lake Wabamun, Alta.	1981	56	9		46		Mitchell, 1985	
262	Duffin Creek ,Ont., station #3	1973-1975	49	11	17.2			Hill, 1981	
79.13	Ag-2, S. Ontario	1975-1976	58.7	40	6	840	652	Coote *et al.*, 1982	
50.8	Ag-1, S. Ontario	1975-1976	89	150	36	2200	1635	Coote *et al.*, 1982	
62	Ag-3, S. Ontario	1975-1976	71.7	80	36	2920	2631	Coote *et al.*, 1982	
18.6	Ag-4, S. Ontario	1975-1976	54	90	33	1900	1547	Coote *et al.*, 1982	
30	Ag-5, S. Ontario	1975-1976	55.1	80	23	2720	2331	Coote *et al.*, 1982	
19.9	Ag-13, S. Ontario	1975-1976	74.4	100	33	2350	2057	Coote *et al.*, 1982	
0.163	Watershed No. 109, Rhode River, MD	1981	64	15.6				Vaithiyanathan and Correll, 1992	estimated from a graph
0.163	Watershed No. 109, Rhode River, MD	1982	64	104				Vaithiyanathan and Correll, 1992	estimated from a graph
0.163	Watershed No. 109, Rhode River, MD	1984	64	260				Vaithiyanathan and Correll, 1992	estimated from a graph
0.163	Watershed No. 109, Rhode River, MD	1985	64	104				Vaithiyanathan and Correll, 1992	estimated from a graph
0.163	Watershed No. 109, Rhode River, MD	1986	64	10.4				Vaithiyanathan and Correll, 1992	estimated from a graph
0.163	Watershed No. 109, Rhode River, MD	1987	64	260				Vaithiyanathan and Correll, 1992	estimated from a graph
45.9	Lamb Creek, Wisconsin	1973	50	18.4	2.8	250	39	Clesceri *et al.*, 1986	
143.2	Paint Creek, Wisconsin	1973	56	18.7	4.5	412	203	Clesceri *et al.*, 1986	
8.9	Friday Creek, Wisconsin	1973	55	19.6	6	316	121	Clesceri *et al.*, 1986	
83.1	Fenwood Creek, Wisconsin	1973	58	23.6	4.7	432	162	Clesceri *et al.*, 1986	
59.3	Freeman creek, Wisconsin	1973	63	15.1	4.4	561	309	Clesceri *et al.*, 1986	
1.36	Station No. 1, Iowa lakes, Dickson County, Iowa	1971	74	286				Jones *et al.*, 1976	
1.09	Station No. 5, Iowa lakes, Dickson County, Iowa	1971	92	47				Jones *et al.*, 1976	
1.42	Station No. 6, Iowas lakes, Dickson County, Iowa	1971	77	36				Jones *et al.*, 1976	
4.95	Station No. 8, Iowa lakes, Dickson County, Iowa	1971	85	96				Jones *et al.*, 1976	
6.56	Station No. 9, Iowa lakes, Dickson County, Iowa	1971	92	47				Jones *et al.*, 1976	
1.99	Station No. 10, Iowa lakes, Dickson lakes, Iowa	1971	62	46				Jones *et al.*, 1976	
6.51	Station No. 11, Iowa lakes, Dickson lakes, Iowa	1971	85	23				Jones *et al.*, 1976	
11.75	Station No. 18, Iowa lakes, Dickson lakes, Iowa	1971	73	50				Jones *et al.*, 1976	
2.77	Station No. 19, Iowa lakes, Dickson lakes, Iowa	1971	74	72				Jones *et al.*, 1976	
7.32	Station No. 22, Iowa lakes, Dickson lakes, Iowa	1971	73	32				Jones *et al.*, 1976	

1.25	Station No. 23, Iowa lakes, Dickson lakes, Iowa	1971	69	38				Jones *et al.*, 1976
13.41	Station No. 29, Iowa lakes, Dickson lakes, Iowa	1971	56	19				Jones *et al.*, 1976
1.45	Station No. 33, Iowa lakes, Dickson lakes, Iowa	1971	55	38				Jones *et al.*, 1976
7.02	Station No. 38, Iowa lakes, Dickson lakes, Iowa	1971	72	129				Jones *et al.*, 1976
11.64	Station No. 40, Iowa lakes, Dickson lakes, Iowa	1971	79	68				Jones *et al.*, 1976
7.42	Station No. 41, Iowa lakes, Dickson lakes, Iowa	1971	90	62				Jones *et al.*, 1976
39.17	Station No. 48, Iowa lakes, Dickson lakes, Iowa	1971	73	15				Jones *et al.*, 1976
1.36	Station No. 1, Iowa lakes, Dickson County, Iowa	1972	74	68				Jones *et al.*, 1976
1.09	Station No. 5, Iowa lakes, Dickson County, Iowa	1972	92	24				Jones *et al.*, 1976
1.42	Station No. 6, Iowas lakes, Dickson County, Iowa	1972	77	4				Jones *et al.*, 1976
4.95	Station No. 8, Iowa lakes, Dickson County, Iowa	1972	85	45				Jones *et al.*, 1976
6.56	Station No. 9, Iowa lakes, Dickson County, Iowa	1972	92	27				Jones *et al.*, 1976
1.99	Station No. 10, Iowa lakes, Dickson lakes, Iowa	1972	62	41				Jones *et al.*, 1976
6.51	Station No. 11, Iowa lakes, Dickson lakes, Iowa	1972	85	53				Jones *et al.*, 1976
11.75	Station No. 18, Iowa lakes, Dickson lakes, Iowa	1972	73	10				Jones *et al.*, 1976
2.77	Station No. 19, Iowa lakes, Dickson lakes, Iowa	1972	74	21				Jones *et al.*, 1976
7.32	Station No. 22, Iowa lakes, Dickson lakes, Iowa	1972	73	23				Jones *et al.*, 1976
1.25	Station No. 23, Iowa lakes, Dickson lakes, Iowa	1972	69	24				Jones *et al.*, 1976
13.41	Station No. 29, Iowa lakes, Dickson lakes, Iowa	1972	56	6				Jones *et al.*, 1976
1.45	Station No. 33, Iowa lakes, Dickson lakes, Iowa	1972	55	10				Jones *et al.*, 1976
7.02	Station No. 38, Iowa lakes, Dickson lakes, Iowa	1972	72	60				Jones *et al.*, 1976
11.64	Station No. 40, Iowa lakes, Dickson lakes, Iowa	1972	79	23				Jones *et al.*, 1976
7.42	Station No. 41, Iowa lakes, Dickson lakes, Iowa	1972	90	14				Jones *et al.*, 1976
39.17	Station No. 48, Iowa lakes, Dickson lakes, Iowa	1972	73	17				Jones *et al.*, 1976
1.36	Station No. 1, Iowa lakes, Dickson County, Iowa	1973	74	89				Jones *et al.*, 1976
1.09	Station No. 5, Iowa lakes, Dickson County, Iowa	1973	92	9				Jones *et al.*, 1976
1.42	Station No. 6, Iowas lakes, Dickson County, Iowa	1973	77	17				Jones *et al.*, 1976
4.95	Station No. 8, Iowa lakes, Dickson County, Iowa	1973	85	64				Jones *et al.*, 1976
6.56	Station No. 9, Iowa lakes, Dickson County, Iowa	1973	92	27				Jones *et al.*, 1976
1.99	Station No. 10, Iowa lakes, Dickson lakes, Iowa	1973	62	21				Jones *et al.*, 1976
6.51	Station No. 11, Iowa lakes, Dickson lakes, Iowa	1973	85	18				Jones *et al.*, 1976
11.75	Station No. 18, Iowa lakes, Dickson lakes, Iowa	1973	73	43				Jones *et al.*, 1976
2.77	Station No. 19, Iowa lakes, Dickson lakes, Iowa	1973	74	34				Jones *et al.*, 1976
7.32	Station No. 22, Iowa lakes, Dickson lakes, Iowa	1973	73	48				Jones *et al.*, 1976
1.25	Station No. 23, Iowa lakes, Dickson lakes, Iowa	1973	69	18				Jones et al., 1976
13.41	Station No. 29, Iowa lakes, Dickson lakes, Iowa	1973	56	18				Jones *et al.*, 1976
1.45	Station No. 33, Iowa lakes, Dickson lakes, Iowa	1973	55	39				Jones *et al.*, 1976
7.02	Station No. 38, Iowa lakes, Dickson lakes, Iowa	1973	72	67				Jones *et al.*, 1976
11.64	Station No. 40, Iowa lakes, Dickson lakes, Iowa	1973	79	33				Jones *et al.*, 1976
7.42	Station No. 41, Iowa lakes, Dickson lakes, Iowa	1973	90	55				Jones *et al.*, 1976
39.17	Station No. 48, Iowa lakes, Dickson lakes, Iowa	1973	73	16				Jones *et al.*, 1976
20.09	Colorado, Cherry Creek Reservoir, 0804E1	1974	>75%	0.6	0.2	8.2	0.6	Omnerick, 1977
15.85	Idaho, Cour D'Alene Lake, 16031L	1974	>75%	10.8	7	489.6	419.1	Omnerick, 1977
52.92	Idaho, Cour D'Alene Lake, 16031M	1974	>75%	12.1	6.3	208.9	124.4	Omnerick, 1977
23.45	Idaho, Cour D'Alene Lake, 16031N	1974	>75%	8.1	3.6	105.9	69.1	Omnerick, 1977
62.64	Idaho, Cour D'Alene Lake, 16031P	1974	>75%	10.9	3	213	125.4	Omnerick, 1977
101.81	Iowa	1974	>75%	25.6	8.5	1246.4	1096.5	Omnerick, 1977
54.44	Iowa	1974	>75%	44.6	14.4	1315.1	1112.2	Omnerick, 1977
13.96	Iowa	1974	>75%	39	15.2	856	529.5	Omnerick, 1977
8.68	Iowa	1974	>75%	21.5	10.7	644.8	439.7	Omnerick, 1977
21.42	Iowa	1974	>75%	25.2	10.7	1358.4	1174.3	Omnerick, 1977
51.37	Iowa	1974	>75%	45.5	19.6	984.2	730	Omnerick, 1977
11.08	Iowa	1974	>75%	29.3	16.6	1848	1635	Omnerick, 1977
65.89	Iowa	1974	>75%	56.7	12.5	1395.8	1119.4	Omnerick, 1977
17.6	Iowa	1974	>75%	32.9	12.2	796.4	594.9	Omnerick, 1977
30.58	Iowa	1974	>75%	73.8	14.3	1300.1	1004.4	Omnerick, 1977
34.31	Iowa	1974	>75%	35	11.4	686.4	459.7	Omnerick, 1977
27.65	Iowa	1974	>75%	17.2	6.6	1186.9	1021.9	Omnerick, 1977
20.81	Iowa	1974	>75%	25	9.1	1191.6	999.7	Omnerick, 1977
21.22	Iowa	1974	>75%	30	14	1762.2	1283.3	Omnerick, 1977
30.67	Iowa	1974	>75%	8.6	5.2	1635.9	1492.3	Omnerick, 1977
25.77	Kansas	1974	>75%	25.3	10.8	423.1	163	Omnerick, 1977
17.31	Kansas	1974	>75%	8.7	4	290	127.6	Omnerick, 1977
29.28	Kansas	1974	>75%	15.1	2.4	243	77.9	Omnerick, 1977
195.48	Kansas	1974	>75%	9	6.6	60.5	12.4	Omnerick, 1977

15.56	Kansas	1974	>75%	12.5	4.1	278.1	147.9	Omnerick, 1977
35.9	Kansas	1974	>75%	21.7	4.4	299.5	142.5	Omnerick, 1977
17.77	Kansas	1974	>75%	24.7	9.2	404.4	231.8	Omnerick, 1977
58.43	Kentucky	1974	>75%	9.1	4.7	496.5	339.4	Omnerick, 1977
61.64	Missouri	1974	>75%	23.7	3.4	382	110.7	Omnerick, 1977
30.92	Missouri	1974	>75%	43.5	39	488.2	141.4	Omnerick, 1977
10.56	Missouri	1974	>75%	29.8	4.6	470.5	157.8	Omnerick, 1977
40.46	Missouri	1974	>75%	25.7	3.8	411.5	101.9	Omnerick, 1977
19.13	Nebraska	1974	>75%	42.5	31.1	313.3	219.7	Omnerick, 1977
13.29	Nebraska	1974	>75%	23	16.4	230.7	113.1	Omnerick, 1977
37.25	Nebraska	1974	>75%	27.5	19.8	151.5	78	Omnerick, 1977
6.97	North Dakota	1974	>75%	9.7	7.5	57.3	12.2	Omnerick, 1977
20.52	North Dakota	1974	>75%	8.9	4.1	94.3	11.5	Omnerick, 1977
26.06	North Dakota	1974	>75%	3.8	2.7	41.4	14.8	Omnerick, 1977
41.56	North Dakota	1974	>75%	8.9	3.5	92.5	29.7	Omnerick, 1977
36.33	North Dakota	1974	>75%	6.7	2.7	59.9	16.4	Omnerick, 1977
107.03	Oklahoma	1974	>75%	2.8	0.7	74.3	30.8	Omnerick, 1977
39.63	Oklahoma	1974	>75%	6	0.6	77.5	32.8	Omnerick, 1977
88.59	Oklahoma	1974	>75%	12.2	3.6	192.4	21.9	Omnerick, 1977
136.42	Oklahoma	1974	>75%	10.7	2.9	95.3	12.2	Omnerick, 1977
42.71	Oklahoma	1974	>75%	14	4.3	110.8	30.3	Omnerick, 1977
23.59	Oklahoma	1974	>75%	1.2	0.4	34.2	12.8	Omnerick, 1977
6.39	Oregon	1974	>75%	11.2	4.6	535	356.4	Omnerick, 1977
46.93	Oregon	1974	>75%	22.3	7.4	239.2	77.1	Omnerick, 1977
4.02	Oregon	1974	>75%	15.8	9.2	209.1	61.7	Omnerick, 1977
6.67	Oregon	1974	>75%	16.3	10	315.4	200.4	Omnerick, 1977
58.47	Texas	1974	>75%	10.1	3.8	316.8	64	Omnerick, 1977
83.96	Texas	1974	>75%	41.2	5.4	478.7	339.2	Omnerick, 1977
103.48	Texas	1974	>75%	44.5	5.3	294	119.1	Omnerick, 1977
33.15	Texas	1974	>75%	19.1	3.5	280.3	94.5	Omnerick, 1977
44.99	Texas	1974	>75%	12	4.1	185.3	42.9	Omnerick, 1977
19.38	Texas	1974	>75%	6.3	3.6	543.4	328.5	Omnerick, 1977
45.45	Texas	1974	>75%	7.1	2.3	221.8	36.2	Omnerick, 1977
51.34	Washington	1974	>75%	10.2	4.8	175.5	147.1	Omnerick, 1977
37.39	Washington	1974	>75%	5.7	2.2	125.7	105.6	Omnerick, 1977
25.9	Washington	1974	>75%	24.5	4.6	175.8	106	Omnerick, 1977
2.28	Delaware, Killen Pond, 1002B1	1973	>75%	69.7	31.5	1517.6	1035.8	Omnerick, 1977
134.89	Illinois	1973	>75%	47.7	20.6	411.4	147.3	Omnerick, 1977
59.39	Illinois	1973	>75%	53.6	18.3	452.9	144.2	Omnerick, 1977
20.9	Illinois	1973	>75%	23.9	8	1255.2	999	Omnerick, 1977
109.06	Illinois	1973	>75%	30.5	15.6	1055.9	977.1	Omnerick, 1977
53.54	Illinois	1973	>75%	18.4	6.4	1371.4	1168	Omnerick, 1977
45.56	Illinois	1973	>75%	15.1	5	1067.9	953.6	Omnerick, 1977
26.37	Illinois	1973	>75%	30.6	17	1043.4	920.2	Omnerick, 1977
57.06	Illinois	1973	>75%	21.6	6.6	1170.1	1060.8	Omnerick, 1977
21.63	Illinois	1973	>75%	22.2	7.7	1216.8	1058.7	Omnerick, 1977
51.13	Illinois	1973	>75%	33.8	17.2	1389.1	1159.8	Omnerick, 1977
30.82	Illinois	1973	>75%	27.8	5.1	415.7	133.2	Omnerick, 1977
28.21	Illinois	1973	>75%	23.4	14.1	1020.5	892.1	Omnerick, 1977
40.64	Illinois	1973	>75%	18.2	6.4	1292	1194.4	Omnerick, 1977
144.39	Illinois	1973	>75%	42.9	20.7	1476.5	1291.6	Omnerick, 1977
119.3	Illinois	1973	>75%	53.5	27	1404.1	1181.8	Omnerick, 1977
60.74	Illinois	1973	>75%	22.3	10.1	1484.6	1322.8	Omnerick, 1977
98.52	Illinois	1973	>75%	18.6	5.4	1449.1	1413.8	Omnerick, 1977
13.49	Illinois	1973	>75%	18.7	5.5	1688.4	1566.2	Omnerick, 1977
24.29	Illinois	1973	>75%	15.4	2.9	1524.3	1411.3	Omnerick, 1977
29.73	Illinois	1973	>75%	29.2	3.6	1688.2	1498.5	Omnerick, 1977
43.9	Illinois	1973	>75%	14.2	3.2	1567.8	1425.1	Omnerick, 1977
35.41	Illinois	1973	>75%	12.5	2.6	1460.5	1342.3	Omnerick, 1977
36.23	Illinois	1973	>75%	23.2	9.4	1268.5	1132.7	Omnerick, 1977
12.61	Illinois	1973	>75%	10.4	7.6	1222.2	1046.2	Omnerick, 1977
17.38	Illinois	1973	>75%	24.2	9.2	1299.4	1119.1	Omnerick, 1977
32.17	Illinois	1973	>75%	35.7	18.2	1498.1	1348.1	Omnerick, 1977
138.15	Illinois	1973	>75%	25	10.4	1450.8	1278.3	Omnerick, 1977
90.86	Illinois	1973	>75%	37.8	8.9	549	118.5	Omnerick, 1977

11.47	Illinois	1973	>75%	31.6	17.1	435	170.9	Omnerick, 1977
10.54	Illinois	1973	>75%	30.3	12.4	457.8	142	Omnerick, 1977
4.53	Illinois	1973	>75%	39.9	14.4	440.3	120.1	Omnerick, 1977
3.16	Illinois	1973	>75%	62.5	26.5	607.2	288.2	Omnerick, 1977
23.88	Indiana	1973	>75%	29.2	14.3	1562.1	1343.7	Omnerick, 1977
7.59	Indiana	1973	>75%	50	34.3	1520	1224.5	Omnerick, 1977
25.62	Indiana	1973	>75%	31	11.2	772.8	382.6	Omnerick, 1977
18.36	Indiana	1973	>75%	28	15.2	1688.1	1381.2	Omnerick, 1977
48.02	Indiana	1973	>75%	24.4	15.7	1402.4	1168.1	Omnerick, 1977
4.53	Indiana	1973	>75%	12	6.4	1405.7	1181	Omnerick, 1977
29.81	Indiana	1973	>75%	21.6	5.9	823.8	452.3	Omnerick, 1977
9.27	Indiana	1973	>75%	16.5	4.3	896.5	516.5	Omnerick, 1977
3.81	Indiana	1973	>75%	54	28.1	1566.4	1116.8	Omnerick, 1977
5.52	Indiana	1973	>75%	10	4.3	938.4	634.4	Omnerick, 1977
33.2	Indiana	1973	>75%	23	5.9	972	586.3	Omnerick, 1977
8.18	Indiana	1973	>75%	32.1	13	1572.3	1109.4	Omnerick, 1977
21.89	Indiana	1973	>75%	25.1	8.9	895.8	524.4	Omnerick, 1977
2.15	Indiana	1973	>75%	21.7	2.6	498.7	215.9	Omnerick, 1977
171.3	Michigan	1973	>75%	44.9	14	1302.3	754.7	Omnerick, 1977
144.83	Michigan	1973	>75%	19.8	11	478.7	261.3	Omnerick, 1977
35.02	Minnesota	1973	>75%	3.2	1.1	41.7	16.6	Omnerick, 1977
15.07	Minnesota	1973	>75%	2.2	1.3	130	108.4	Omnerick, 1977
62.19	Minnesota	1973	>75%	3	1.4	58.1	20.4	Omnerick, 1977
51.9	Minnesota	1973	>75%	41.6	21.1	387	162.7	Omnerick, 1977
9.382	Minnesota	1973	>75%	25.9	11.2	594.2	297	Omnerick, 1977
6.24	Minnesota	1973	>75%	6	2.7	283.6	185.5	Omnerick, 1977
88.34	Minnesota	1973	>75%	30.8	17.7	702.7	406.8	Omnerick, 1977
176.79	Minnesota	1973	>75%	34.2	10.7	382.9	196.8	Omnerick, 1977
78.3	Minnesota	1973	>75%	16	11.9	397	287.7	Omnerick, 1977
15.07	Minnesota	1973	>75%	12.2	7.1	417.1	308.7	Omnerick, 1977
6.29	NewYork	1973	>75%	20.5	11.2	699.9	441.6	Omnerick, 1977
44.21	Ohio	1973	>75%	50.6	20.9	849.9	653.3	Omnerick, 1977
83.99	Ohio	1973	>75%	36.8	5.8	836.7	592.8	Omnerick, 1977
15.51	Ohio	1973	>75%	47.2	16.3	1208.2	844.5	Omnerick, 1977
31.03	Ohio	1973	>75%	36.9	10.4	1074.7	674.7	Omnerick, 1977
19.76	Ohio	1973	>75%	8.8	4.2	477.3	257.7	Omnerick, 1977
42.17	Ohio	1973	>75%	10.7	6.4	535.6	306.6	Omnerick, 1977
31.57	Ohio	1973	>75%	21.4	7.3	1164.3	834.8	Omnerick, 1977
15.41	Ohio	1973	>75%	27	12.3	1021.6	793.5	Omnerick, 1977
52.89	Ohio	1973	>75%	73.7	20.4	642.5	156.3	Omnerick, 1977
5	Ohio	1973	>75%	81.4	17.4	617.6	120.7	Omnerick, 1977
32.3	Ohio	1973	>75%	25.3	10	730.5	430.2	Omnerick, 1977
18.6	Ohio	1973	>75%	62.3	28	1290.1	921.2	Omnerick, 1977
45.84	Ohio	1973	>75%	96	44.8	1179.3	746.5	Omnerick, 1977
47.22	Ohio	1973	>75%	83.5	38.2	1176.6	786.5	Omnerick, 1977
8.62	Ohio	1973	>75%	74.4	24.4	1483	976.3	Omnerick, 1977
12.1	Ohio	1973	>75%	136	112	1549	1262.9	Omnerick, 1977
6.55	Ohio	1973	>75%	30	8.4	1264.4	874.4	Omnerick, 1977
27.4	Ohio	1973	>75%	19.6	8.7	724.4	470.2	Omnerick, 1977
15.15	Ohio	1973	>75%	35	10.3	884.7	491.2	Omnerick, 1977
21.24	Ohio	1973	>75%	14.4	5.2	1402	1156.3	Omnerick, 1977
26.31	South Dakota	1973	>75%	6.1	2.7	45.1	13.1	Omnerick, 1977
37.17	South Dakota	1973	>75%	4.3	2.8	58.2	30.1	Omnerick, 1977
28.38	South Dakota	1973	>75%	1.9	0.8	92.5	40.9	Omnerick, 1977
28.45	South Dakota	1973	>75%	8.2	3	54.5	28.3	Omnerick, 1977
47.23	South Dakota	1973	>75%	5.9	3.8	55	14.8	Omnerick, 1977
20.25	South Dakota	1973	>75%	9.7	7.5	75.2	38.9	Omnerick, 1977
36.26	South Dakota	1973	>75%	9.5	3.6	36.9	15.2	Omnerick, 1977
43.8	Virginia	1973	>75%	5.7	2.6	356.1	258.2	Omnerick, 1977
15.05	Wisconsin	1973	>75%	29.5	12.2	465.7	248.1	Omnerick, 1977
6.55	Wisconsin	1973	>75%	26.6	13.3	487.9	370.2	Omnerick, 1977
44.34	Wisconsin	1973	>75%	23.6	12.3	440.7	278.2	Omnerick, 1977
51.02	Wisconsin	1973	>75%	22.1	12.1	389.4	214.7	Omnerick, 1977
25.72	Wisconsin	1973	>75%	14.5	7.4	554	511	Omnerick, 1977
87.31	Wisconsin	1973	>75%	31.2	13.3	582.6	411.5	Omnerick, 1977
4.3	Wisconsin	1973	>75%	29.9	20.7	1638.9	1432.3	Omnerick, 1977

APPENDIX F. Total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), dissolved inorganic nitrogen (DIN) export coefficients for grazed or pastured basins of North America.

				Export Coefficient (kg/km²/y)					
Watershed Area (km2)	Watershed Location	Sampling Date	Land use % Pasture	TP	SRP	TN	DIN	Citation	Comments
2.5	Majeau Creek Watershed, M2, Alta.	1981	100	79	39.5	609		Mitchell and Hamilton, 1982	
1.9	Majeau Creek Watershed, M3, Alta.	1981	100	72				Mitchell and Hamilton, 1982	
11.7	Majeau Creek Watershed, M4, Alta.	1981	100	117	58.5	713		Mitchell and Hamilton, 1982	
9	Majeau Creek Watershed, M5, Alta.	1981	100	37	18.5	191		Mitchell and Hamilton, 1982	
5.4	Majeau Creek Watershed, M5a, Alta.	1981	100	20	10	126		Mitchell and Hamilton, 1982	
22.6	Majeau Creek Watershed, M6, Alta.	1981	100	32	26.2	156		Mitchell and Hamilton, 1982	
1.6	Majeau Creek Watershed, M7, Alta.	1981	100	142	116.4	406		Mitchell and Hamilton, 1982	
3.1	Majeau Creek Watershed, M8, Alta.	1981	100	81	40.5	352		Mitchell and Hamilton, 1982	
0.39	Majeau Creek Watershed, M9, Alta.	1981	100	64	32	228		Mitchell and Hamilton, 1982	
0.39	Majeau Creek Watershed, M10, Alta.	1981	100	41	20.5	100		Mitchell and Hamilton, 1982	
50.3	Martin Creek, Ontario	1965	50	20.5				Dillon and Kirchner, 1975	
112.4	Wilton Creek, Ontario	1966	50	21.5	10	350		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1967	50	10	7	250		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1968	50	11	6	375		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1969	50	21	10	350		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1970	50	21.5	8.5	400		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1971	50	21	9	375		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1972	50	17	4.5	325		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1973	50	23	12	485		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario	1974	50	26	11.5	500		Minns and Johnson, 1979	estimated from graph
112.4	Wilton Creek, Ontario		50	14.5	6	400		Minns and Johnson, 1979	estimated from graph
45	Watershed Ag - 14, southern Ontario		66.6	60	23	320		Coote *et al.*, 1982	
1.23	Watershed 196 Coshocton, Ohio	1966	50	3.12		167		Taylor *et al.*, 1971	
1.23	Watershed 196 Coshocton, Ohio	1967	50	8.01		311		Taylor *et al.*, 1971	
1.23	Watershed 196 Coshocton, Ohio	1968	50	6.65		1061		Taylor *et al.*, 1971	
1.23	Watershed 196 Coshocton, Ohio	1969	50	7.67		438		Taylor *et al.*, 1971	
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	15		344		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	16		383		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	13		241		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	12		347		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	70		1805		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	18		1271		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	11		831		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.02	Dairy grazing watershed, Wayneville, North Carolina		100	12		926		Kilmer *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.06	eastern South Dakota		100	25		152		Harms, *et al.*, 1974	Cited in Reckhow *et al.*, 1980
0.01	Coshocton, Ohio		100	360		3085		Chichester *et al.*, 1979	Cited in Reckhow *et al.*, 1980
0.01	Coshocton, Ohio		100	85		2185		Chichester *et al.*, 1979	Cited in Reckhow *et al.*, 1980
0.43	Treynor, Iowa		100	25.1		232		Schuman et al., 1973	Cited in Reckhow et al., 1980
0.43	Treynor, Iowa		100	8.1		47		Schuman *et al.*, 1973	Cited in Reckhow *et al.*, 1980
0.43	Treynor, Iowa		100	51.2		428		Schuman *et al.*, 1973	Cited in Reckhow *et al.*, 1980
0.1	Eatonia, Georgia		100	135				Krebs and Golley, 1977	Cited in Reckhow *et al.*, 1980
3.5	Rhode River watershed, Maryland		100	380				Correll *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	386		684		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	106		543		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	186		923		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	26		133		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	144		202		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	24		95		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	27		230		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	2		15		Menzel *et al.*, 1978	Cited in Reckhow *et al.*, 1980
0.08	Chickasha, Oklahoma		100	490		920		Olness *et al.*, 1980	Cited in Reckhow *et al.*, 1980
0.1	Chickasha, Oklahoma		100	309		472		Olness *et al.*, 1980	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	76		519		Olness *et al.*, 1980	Cited in Reckhow *et al.*, 1980
0.11	Chickasha, Oklahoma		100	20		173		Olness *et al.*, 1980	Cited in Reckhow *et al.*, 1980
15.26	Kansas, Marion Reservoir, 2007D1		50	27.5	4.6	309.9	63.2	Omnerick, 1977	

147.4	Nebraska, Harry D. Struck Reservoir, 3103E1	50	6	1.3	107.8	60.1	Omnerick, 1977
17.28	Nebraska, Lake McConaugay, 3106C1	50	51.3	40.4	785.5	592.4	Omnerick, 1977
33.8	Oklahoma, Fort Supply Reservoir, 4006E1	50	1.6	0.4	28.9	9.6	Omnerick, 1977
62.54	Oklahoma, Foss Oak Reservoir, 4007B1	50	6.8	1	54.4	8	Omnerick, 1977
28.35	Oklahoma, Keystone Reservoir, 4011B1	50	4	0.9	118.2	10.8	Omnerick, 1977
49.7	Oklahoma, Oologah Lake, 4012D2	50	7.9	5.6	269.7	46.8	Omnerick, 1977
34.7	Texas, Eagle Mountain Reservoir, 4813E1	50	4.6	1	117.8	21.2	Omnerick, 1977
158.93	Texas, Stillhouse Hollow Reservoir,4831C1	50	1.8	0.5	41.6	12.7	Omnerick, 1977
44.67	Texas, Texoma Lake, 4834F1	50	4.7	2.2	150.8	13.2	Omnerick, 1977
21.15	Texas, Travis Lake, 4835D1	50	2	0.8	111.2	57	Omnerick, 1977
22.75	California, Don Pedro Reservoir, 0606C1	50	5.3	1.4	324	44.1	Omnerick, 1977
48.51	California, Tulloch Reservoir, 0624B1	50	3.5	1.7	231.7	100.7	Omnerick, 1977
64.23	Montana, Tongue River Reservoir, 3014E1	50	5.7	0.6	77.6	16.1	Omnerick, 1977
56.24	Montana, Tongue River Reservoir, 3014F1	50	4.5	1	65	9.1	Omnerick, 1977
28.38	Nebraska, Harry D. Strunk Reservoir, 3103B1	50	4.8	2.4	146.1	96.9	Omnerick, 1977
57.93	North Dakota, Sakakawea Reservoir, 3812R2	50	1.6	0.3	17	1.5	Omnerick, 1977
99.55	Texas, Lyndon B. Johnson Lake, 4821E1	50	0.7	0.5	43	7.8	Omnerick, 1977
20.16	Texas, Palestine Reservoir, 4824F1	50	10.6	3.8	204.4	87.4	Omnerick, 1977
24.29	Texas, Travis Lake, 4835B1	50	1.4	0.6	80.2	42.2	Omnerick, 1977
78.45	Texas, Travis Lake, 4835F1	50	0.1	0.1	6.3	3.4	Omnerick, 1977
60.9	Utah, Bear Lake, 4901K1	50	0.7	0.2	13.7	3.4	Omnerick, 1977
13.08	Wyoming, Viva Naughton Reservoir,5612B1	50	11.3	5.8	225.3	96.1	Omnerick, 1977
42.91	California, Tulloch Reservoir, 0624B1	75	15.3	13.3	429.8	104.7	Omnerick, 1977
44.21	Kansas, Toronto Reservoir, 2013D1	75	13.2	2.7	271.9	65	Omnerick, 1977
19.18	Kansas, Tuttle Creek Reservoir, 201418	75	4	1.1	87.1	20.9	Omnerick, 1977
101.59	Montana, Tongue River Reservoir, 3014D1	75	2	0.3	44.3	6	Omnerick, 1977
172.3	Nebraska, Harry D. Strunk Reservoir, 3103G1	75	6.3	4.1	125.3	87.2	Omnerick, 1977
7.05	Nevada, Topaz Lake, 3205C1	75	32.4	6.8	253.6	28.5	Omnerick, 1977
44.52	New Mexico, Ute Reservoir, 3509C1	75	1.7	0.4	31.8	4.8	Omnerick, 1977
14.46	Oregon, Brownlee Reservoir, 4101F1	75	6.1	4.6	58.7	15.4	Omnerick, 1977
31.73	Oregon, Brownlee Reservoir, 4101K1	75	3.9	2.9	43.3	20.5	Omnerick, 1977
42.59	Oregon, Brownlee Reservoir, 4101G1	75	4.4	3.2	51	14.1	Omnerick, 1977
20.45	Oregon, Owyhee Reservoir,4105D1	75	9.6	8.7	116.7	45.6	Omnerick, 1977
23.34	Texas, Lyndon B. Johnson Lake, 4821B1	75	0.7	0.4	38.2	5.7	Omnerick, 1977
63.39	Texas, Lyndon B. Johnson Lake, 4821C1	75	0.8	0.4	37.6	6.9	Omnerick, 1977
25.03	Texas, Lyndon B. Johnson Lake, 4821H1	75	0.8	0.4	34.3	14.6	Omnerick, 1977
50.06	Texas, Travis Lake, 4835E1	75	1.9	1.1	70.4	12.8	Omnerick, 1977
11.64	Utah, Bear Lake, 4901G1	75	5.2	0.5	57.4	31.5	Omnerick, 1977
119.51	Wyoming, Keyhole Reservoir, 5608C1	75	2	0.3	10.5	2	Omnerick, 1977

APPENDIX G. Test of slope of log nutrient yield (kg/y) vs log drainage area (km^2) is different from 1. TP = total phosphorus, SRP = soluble reactive phosphorus, TN = total nitrogen, NA = North America, Can = Canada, AB = Alberta, n= number of observations, b = predicted slope and *t* = test statistic.

TP			n	b	*t*	*P* value	Range (km^2)
	Forest	NA	310	1.036	1.92	> 0.05	0.0001-245454
		Can	122	1.044	2.01	< 0.05	0.070-245454
		AB	27	0.9895	0.15	> 0.5	0.67-281
	Crop	NA	250	0.8769	3.28	< 0.002	0.16-262
		Can	33	1.1083	1.07	> 0.2	0.71-262
		AB	26	0.9636	0.33	> 0.5	0.71-89.34
	Pasture	NA	94	0.7176	5.94	< 0.001	0.01-172.3
		Can	22	0.7267	4.74	< 0.001	0.39-112.4
		AB	10	0.9049	0.61	> 0.2	0.39-22.6
SRP							
	Forest	NA	224	0.9717	1.29	> 0.2	0.0149-12548.7
		Can	57	0.9536	1.41	> 0.1	3.089-12548.7
		AB	17	0.9143	0.75	> 0.2	3.089-281
	Crop	NA	181	0.8489	2.51	< 0.02	0.705-262
		Can	21	0.9688	0.35	> 0.5	0.705-262
		AB	14	0.8543	1.31	> 0.2	0.705-89.34
	Pasture	NA	60	0.4313	3.92	< 0.001	0.39-172.3
		Can	20	0.6941	4.43	< 0.001	0.39-112.4
		AB	9	0.9505	0.26	> 0.5	0.39-22.6
TN							
	Forest	NA	205	1.0349	0.88	> 0.2	0.06-1546
		Can	37	1.0508	0.736	> 0.2	0.63-90.5
		AB	25	1.0505	0.481	> 0.5	0.67-90.5
	Crop	NA	192	1.1806	2.49	< 0.02	0.71-195.48
		Can	32	1.40508	2.86	< 0.01	0.71-89.34
		AB	26	1.0728	0.65	> 0.5	0.71-89.34
	Pasture	NA	90	0.8088	5.18	< 0.001	0.01-172.3
		Can	20	1.0977	1.81	> 0.05	0.39-112.4
		AB	9	1.0844	0.47	> 0.5	0.39-22.6

APPENDIX H. Areas and TP, SRP and TN loads for forested, cropland, pastured and barren or water-covered subdivisions with the Athabasca River drainage basin.

Areas and TP, SRP and TN loads for forested subdivisions within the Athabasca River drainage basin. Calculations based on export coefficients of 10, 5 and 135 kg/km^2/y for TP, SRP and TN, respectively. Loads for subdivision 07BF-J corrected for retention in Lesser Slave Lake (see Section 4.2.1.1).

Subdivision	Forested Area (km^2)	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
07AA	4548	45480	22740	613980
07AB	1004	10040	5020	135540
07AC	5675	56750	28375	766125
07AD	2154	21540	10770	290790
07AE	2850	28500	14250	384750
07AF	4778	47780	23890	645030
07AG	4718	47180	23590	636930
07AH	4511	45110	22555	608985
07BA	3675	36750	18375	496125
07BB	1914	19140	9570	258390
07BC	1146	11460	5730	154710
07BD	2559	25590	12795	345465
07BE	2243	22430	11215	302805
07BF-J	12368	104134	58581	834080
07BK	6581	65810	32905	888435
07CA	7091	70910	35455	957285
07CB	9796	97960	48980	1322460
07CC	5805	58050	29025	783675
07CD	17148	171480	85740	2314980
07CE	12783	127830	63915	1725705
07DA	9285	92850	46425	1253475
07DB	5682	56820	28410	767070
07DC	6242	62420	31210	842670
07DD	8430	84300	42150	1138050
Total	**142986**	**1410314**	**711671**	**18467510**

Areas and TP, SRP and TN loads for cropland subdivisions within the Athabasca River drainage basin. Calculations based on export coefficients of 25, 15 and 150 kg/km^2/y for TP, SRP and TN, respectively. Loads for subdivision 07BF-J corrected for retention in Lesser Slave Lake (see Section 4.2.1.1).

Subdivision	Crop Land Area (km^2)	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
07AH	144	3600	2160	21600
07BB	11	275	165	1650
07BC	2323	58075	34845	348450
07BD	173	4325	2595	25950
07BE	594	14850	8910	89100
07BF-J	450	9473	6395	33728
07CA	709	17725	10635	106350
07CB	293	7325	4395	43950
Total	**4697**	**115648**	**70100**	**670778**

Areas and TP, SRP and TN loads for pastured subdivisions within the Athabasca drainage basin. Calculations based on export coefficients of 50, 25 and 300 kg/km^2/y for TP, SRP and TN, respectively. Loads for subdivision 07BF-J corrected for retention in Lesser Slave Lake (see Section 4.2.1.1).

Subdivisions	Pasture Land Area (km^2)	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
07AG	8	400	200	2400
07AH	176	8800	4400	52800
07BA	119	5950	2975	35700
07BB	3929	196450	98225	1178700
07BC	272	13600	6800	81600
07BD	64	3200	1600	19200
07BE	32	1600	800	9600
07CB	37	1850	925	11100
07CA	48	2400	1200	14400
Total	**4685**	**234250**	**117125**	**1405500**

Areas and atmospheric TP, SRP and TN loading to barren land or icefields and waterbodies in the Athabasca drainage basin. Calculations bases on export coefficients of 20, 10 and 400 kg/km^2/y for TP, SRP and TN, respectively.

Subdivision	Water, Barren Land and Icefields area (km^2)	TP Load (kg/y)	SRP Load (kg/y)	TN Load (kg/y)
07AA	2878	57560	28780	1151200
07AB	649	12980	6490	259600
07AC	253	5060	2530	101200
07AD	125	2500	1250	50000
07AE	101	2020	1010	40400
07AF	118	2360	1180	47200
07AH	80	1600	800	32000
07BB	133	2660	1330	53200
07BC	3	60	30	1200
07BD	146	2920	1460	58400
07BE	112	2240	1120	44800
07BF-J	1310	22060	12410	261800
07BK	64	1280	640	25600
07CA	381	7620	3810	152400
07CB	437	8740	4370	174800
07CC	154	3080	1540	61600
07CD	349	6980	3490	139600
07CE	340	6800	3400	136000
07DA	277	5540	2770	110800
07DC	59	1180	590	23600
07DD	213	4260	2130	85200
Total	**8182**	**159500**	**81130**	**3010600**

APPENDIX I. Areas and TP, SRP and TN loads for forested, cropland, and barren or water-covered subdivisions in the Wapiti River drainage basin.

Areas and TP, SRP and TN loads for forested subdivisions within the Wapiti River drainage basin. Calculations based on export coefficients of 10, 5 and 135 kg/km^2/y for TP, SRP and TN, respectively.

Subdivision	Forested Area (km^2)	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
07GC	6685	66850	33425	902475
07GD	2176	21760	10880	293760
07GE	2018	20180	10090	272430
Total	**10879**	**108790**	**54395**	**1468665**

Areas and TP, SRP and TN loads for cropland subdivisions within the Wapiti River drainage basin. Calculations based on export coefficients of 25, 15 and 150 kg/km^2/y for TP, SRP and TN, respectively.

Subdivision	Cropland Area (km^2)	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
07GC	72	1800	1080	10800
07GD	1065	26625	15975	159750
07GE	2040	51000	30600	306000
Total	**3177**	**79425**	**47655**	**476550**

Areas and atmospheric TP, SRP and TN loading to barren land and waterbodies. Calculations based on export coefficients of 20, 10 and 400 kg/km^2/y for TP, SRP and TN, respectively.

Subdivision	Water, Barren Land and Icefields	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
07GC	359	7180	3590	143600
07GD	5	100	50	2000
07GE	48	960	480	19200
Total	**412**	**8240**	**4120**	**164800**

APPENDIX J. Areas and TP, SRP and TN loads for forested, cropland, and barren or water-covered subdivisions in the Smoky River (including the Wapiti River) drainage basin.

Areas and TP, SRP and TN loads for forested subdivisions in the Smoky River (including the Wapiti River) drainage basin. Calculations based on export coefficients of 10, 5 and 135 kg/km²/y for TP, SRP and TN, respectively.

Subdivision	Forested Area (km²)	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
Wapiti	10879	108790	54395	1468665
07GA	4292	42920	21460	579420
07GB	7149	71490	35745	965115
07GF	5296	52960	26480	714960
07GG	7758	77580	38790	1047330
07GH	3012	30120	15060	406620
07GJ	1732	17320	8660	233820
Total	**40118**	**401180**	**200590**	**5415930**

Areas and TP, SRP and TN loads for cropland subdivisions in the Smoky River (including the Wapiti River) drainage basin. Calculations based on export coefficients of 25, 15 and 150 kg/km²/y for TP, SRP and TN, respectively.

Subdivision	Cropland Area (km²)	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
Wapiti	3177	79425	47655	476550
07GF	226	5650	3390	33900
07GG	8	200	120	1200
07GH	1763	44075	26445	264450
07GJ	3187	79675	47805	478050
Total	**8361**	**209025**	**125415**	**1254150**

Areas and atmospheric TP, SRP and TN loading to barren land and waterbodies in the Smoky River (including the Wapiti River) drainage basin.. Calculations based on export coefficients of 20, 10 and 400 kg/km²/y for TP, SRP and TN, respectively.

Subdivision	Water, Barren Land and Icefields	TP load (kg/y)	SRP load (kg/y)	TN load (kg/y)
Wapiti	412	8240	4120	164800
07GA	1203	24060	12030	481200
07GB	93	1860	930	37200
07GG	5	100	50	2000
07GH	107	2140	1070	42800
07GJ	53	1060	530	21200
Total	**1873**	**37460**	**18730**	**749200**