The Effects of Watershed Characteristics and Disturbance History on Lake Water Quality of the Boreal Region of South Eastern Manitoba

by

Kevin Jacobs

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

In partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

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University of Manitoba

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
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The Effects of Watershed Characteristics and Disturbance History on Lake Water Quality of the Boreal Region of South Eastern Manitoba

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

ABSTRACT

Water quality in remote lakes on the east side of Lake Winnipeg was largely unknown. This study was the first attempt at characterizing the baseline conditions in a large number of lakes on the east side of Lake Winnipeg. Water quality of up to 99 boreal shield lakes was sampled by floatplane in 2004 and 2005. Standard physical and chemical water quality data were collected for each lake. Water quality in this region was affected by characteristics of the watershed such as soil type, the proportion of wetlands in the watershed, and forest type. Watershed disturbance such as forest fire and forest harvesting appeared to have a marked influence on water quality. Forest harvesting disturbance and to a lesser extent fire disturbance was associated with the most eutrophic lakes. However, the most dramatic differences compared to reference sites appeared to only occur when a larger proportion of a watershed had been disturbed. The data indicated that if watershed forest harvesting had an impact on water quality it appeared to be of longer duration than that of forest fire.

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1.0 Introduction

The boreal forest is the largest terrestrial ecozone in Canada. It covers approximately 20 percent of the Canadian land mass, contains 43 percent of the commercial forestland, and accounts for 22 percent of the country's freshwater surface area (Environment Canada 2000). Globally the boreal forest or Taiga may contain as many as four million lakes (France et al. 2000). Logging and wildfires are two common perturbations in the boreal forest. In Canada, the rate of forest harvesting has doubled between 1960 and 1990 (Schindler 1998). Currently approximately 400 000 ha are harvested annually in the Boreal Shield. This ecozone also provides 39 percent of Canada's hydroelectric capacity, 75 percent of Canada's iron, nickel, copper, gold, and silver, and widespread cottage development (Environment Canada 2000). The boreal shield is an important economic and recreational region as well as an important traditional land use area for Canadian Aboriginal peoples.

Although the effects of logging and forest fires on flowing water systems have been evaluated to a certain extent, the effects of landscape disturbance on lakes are poorly known (Gibbons and Salo 1973, Gresswell 1999, Tonn et al. 2003). Furthermore, in many areas of the boreal forest there are no data with respect to water quality. This is particularly true for lakes located in eastern Manitoba, especially north of Whiteshell Provincial Park. Data that exist were primarily collected in the late 1970s and early 1980s. This is a major gap in our knowledge of environment of the east side of Lake Winnipeg. Water quality has been identified as a top priority and a major information gap throughout the East Side Lake Winnipeg Planning Initiative (Manitoba Conservation 2002).

Currently, timber harvesting conducted by the Tembec Industries Inc. in eastern Manitoba only minimally account for watershed boundaries and watersheds are for relatively large river systems. Though water quality change is a measure of the sustainability of resource extraction operations, no evaluation has ever been done to determine the magnitude or duration of impacts of forestry or fire on lake water quality in this region.

Generally, the impacts of forest fire and harvest disturbance on water quality have been found to be directly proportional to the catchment area harvested divided by lake size (volume or surface area) (Carignan and Steedman 2000). France et al. (2000) describes how dissolved organic carbon concentrations in Ontario boreal shield lakes were increased by harvesting and wildfire though the direction and extent of observed changes related to topography, percentage wetlands, and extent of the landscape disturbance. Carignan et al. (2000) found nutrient pulses in Quebec lakes following forest fires. Increases in temperature (Steedman et al. 2001) and turbidity (Beaty 1994) would also be expected. However, the magnitude and duration of these effects is largely unknown (Tonn et al 2003). In a comparative study in Quebec of reference, cut and burnt catchments, potassium, total phosphorus, total organic nitrogen and chlorophyll *a* concentrations were higher in lakes with burned watersheds (Carignan et al. 2000), while mobile ions (potassium, chloride, sulphate, nitrate) appeared to be rapidly flushed out of the watershed. Other properties (total phosphorus, organic nitrogen, dissolved organic carbon, light extinction, calcium, and magnesium) showed little change three years after the perturbations. Nutrient concentrations in lakes with harvested watersheds were also above reference concentrations. However, large differences in climate, especially precipitation, and its impact on the return interval of fires and suspected influence on soil moisture patterns, between Quebec and eastern Manitoba make any generalizations or extrapolations between the regions difficult.

To respond to the lack of knowledge on water quality in this region, a water quality survey of approximately 100 lakes occurred in the summers of 2004 and 2005. The study area included both road accessible and remote lakes on the east side of Lake Winnipeg, west of the Ontario border as far south as Whiteshell Provincial Park and north of the Bloodvein River to Dogskin Lake (Map 1). Lakes with reference (little to no harvesting or fire in the watershed within the last 60 years), harvested and burned watersheds were selected using aerial reconnaissance and geographic information system databases of disturbance history.

Preliminary research in eastern Canada appears to indicate that water quality in lakes can be maintained if timber harvesting disturbance is limited to below a certain percentage of a watershed. This percentage has never been explored in Manitoba, even though at least one forestry company (Louisiana Pacific Canada, Swan Valley Operation) has a 30 percent watershed harvest restriction as part of their Environment Act License. The validity of such a restriction is untested.

1.1 Objectives

1. To obtain a broad understanding of baseline water quality conditions in lakes on the east side of Lake Winnipeg

2. To determine the factors influencing lake water quality such as forest type, soil type, proportion of wetlands in a watershed, disturbance type and time since disturbance
3. To identify watersheds sensitive to harvest disturbance as well as identify candidate lakes for long term monitoring
4. To use water quality survey data and disturbance history information to determine if there is rationale for managing watershed harvesting levels

1.2 Hypothesis

I hypothesize that watershed harvesting and forest fire will increase rates of nutrient and sediment transport to lakes, thereby increasing concentrations of nitrogen and phosphorus in lake water. In addition, I expect dissolved organic carbon concentrations to be the highest in lakes with watershed harvesting. I anticipate the magnitude of these differences to be directly proportional to the percentage of watershed disturbed. Furthermore, I expect that lakes with recent disturbance would show the greatest differences relative to the water quality of reference systems and systems disturbed historically.

1. 3 Study Area

The survey occurred in the boreal shield region of eastern Manitoba. The study region the Winnipeg River represented the southern boundary of the study area and Dogskin Lake to the north. The study area included Nopiming and Atikaki Provincial Parks. The Ontario border represented the eastern boundary of the study area and the western boundary was represented by the east shore of Lake Winnipeg (Map 1). The study area boundaries were approximately 155 km north from the community of Pine Falls and 70 km east. The total study area was approximately 10850 km^2.

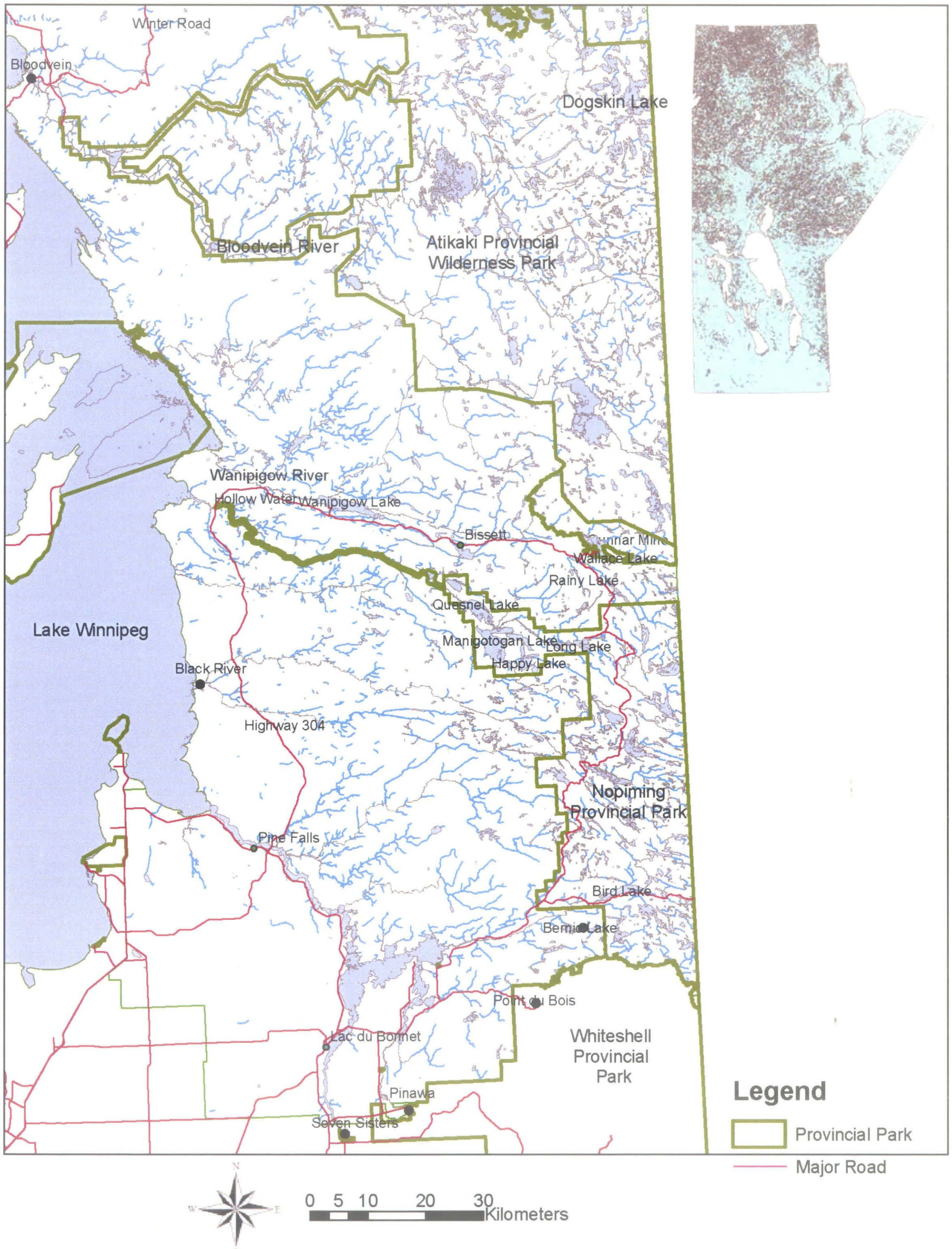

Figure 1: Map of the study area

The total study area is approximately 10850 km^2. Data courtesy Tembec.

1.3.1 Geology/Soils

The study region is located on Canadian Shield Bedrock consisting of gneiss, migmatite, granitoid intrusions and metamorphosed volcanic and sedimentary rocks. It is dominated by granitic accumulation, glacial deposits less than 1 meter deep and poorly drained organic soils. Mineral soils are poorly developed, and are predominantly sandy loam in texture (Ehnes 1998). Soils generally consist of fibrisols, mesisols, dystric brunisols gleysols (Agriculture Canada 1987). Soils are typically shallow, low in nutrient availability and acidic (Environment Canada 2000).

The entire region was covered by ice during the Wisconsin Glaciation and its recession created lakes between ridges and outcrops of granitic rock 9000-8500 years BP (Prest 1970, Teller and Thorleifson 1983). Extensive peat land dominates areas with deeper Agassiz sediments.

Topographic relief is generally low ranging from 373 to 263 m asl. Surface water movement is predominantly east to west with all drainage eventually flowing into Lake Winnipeg and the Hudson Bay Drainage Basin.

1.3.2 Wetlands

Wetland coverage is estimated between 26-50 percent for the western half of the study region and between 6-25 percent for the eastern upland dominated portion (National Wetlands Working Group 1986). Characteristic wetland forms include bogs and fens. Coniferous swamps may be common in areas with shallow peat and gentle slope (Zoltai et al. 1988).

1.3.3 Ecoregions of the study area

The study area is located in the Lac Seul Upland Ecoregion, while two of the study lakes are located in the Lake of the Woods Ecoregion. The Lac Seul Upland Ecoregion extends eastward from Lake Winnipeg in Manitoba to the Albany River in northwestern Ontario (Wilkin 1996). The dominant land cover is coniferous forest with limited areas of mixed forest. Wetlands cover over 25 percent of the ecoregion and are dominated by bogs, fens and coniferous swamp. The population of the ecoregion is approximately 18,400 with the main communities being Red Lake and Sioux Lookout, Ontario. The Lake of the Woods Ecoregion extends from the south end of Lake Winnipeg to the east side of Rainy Lake on the Canada-United States border. Typically, it is more humid and warmer than the more northern Lac Seul Upland Ecoregion. It is marked by warm summers and cold winters. Characteristic vegetation includes trembling aspen, paper birch, jack pine, white spruce, black spruce, and balsam fir. Cooler, poorly drained sites support black spruce and tamarack. The extent of wetlands is variable, being most extensive near Lake of the Woods. Treed bogs and peat margin swamps are the predominant wetland forms. Major communities include Kenora and Dryden, Ontario. The population of this ecoregion is approximately 52,700 (Wilkin 1996).

1.3.4 Vegetation of the region

Vegetation of the study region is characteristic of nutrient poor soils and extensive bogs consisting of a mixture of deciduas and coniferous tree species. Common vegetation species have been summarized elsewhere (Cuthbert 1978, Punter 1994, Ehnes 1995). Scoggan (1957) first described the vegetative zones in this region.

The most common merchantable species are jack pine (*Pinus banksiana)* and black spruce (*Picea nigra)*. Other common tree species include white birch (*Betula papyrifera*), balsam poplar (*Populus balsamifera*), trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca)*, balsam fir *(Abies balsamea)*, and tamarack (*Larix laricina*). Eastern white pine (*Pinus strobes*) is a rare species in the study area.

Understory vegetation consists of woody shrubs such as green and speckled alder (*Alnus crispa, Alnus rugosa*), common blueberry (*Vaccinium myrtilloides)*, common juniper (*Juniperus communis*), beaked hazelnut (*Corylus cornuta*), and red osier dogwood (*Cornus stolonifera*). Examples of herbaceous species include twinflower (*Linnaea borealis*), bunchberry (*Cornus Canadensis*), wild strawberry (*Fragaria virginiana*) and have been described elsewhere (Scoggan 1957, Cuthbert 1978, Punter 1994, Ehnes 1995). Ground cover generally consists of a layer of mosses and lichens e.g. reindeer lichens (*Cladina spp.),* club lichens (*Cladonia* spp), and sphagnum growing on peat, mineral soils or exposed rock. Wild rice (*Zizania aquatica)* is an important plant resource and is harvested in many of the regions shallow lakes.

1.3.5 Fauna of the region

There are 47 mammal species suspected or known to occur within Nopiming Provincial Park, which is representative of the study area (Cuthbert 1978). These include the wolverine (*Gulo gulo*), grey wolf (*Canis lupus*), coyote (*Canis latrans*), black bear (*Ursus americanus*), moose (*Alces alces*), white-tailed deer (*Odocoileus virginianus*) and woodland caribou (*Rangifer tarandus*). Woodland caribou is classified as threatened by the Committee on the Status of Endangered Wildlife in Canada and is protected under the Species at Risk Act. In addition, over 140 bird species occur within the region. Ten species of amphibian and four reptile species are either know or suspected to occur in the study area (Cuthbert 1978, Koonz 1979).

Economically important fish species in this region include walleye (*Stizostedion vitreum*), northern pike (*Esox Lucius*), lake trout (*Salveninus namaycush*), whitefish (*Coregonus clupeaforis*), yellow perch (*Perca flavescens*), and small mouth bass (*Micropterus dolomieui*). Small mouth bass is not an endemic species to the area but was introduced to Shoe Lake (Manitoba Division of Fish Culture 1978) and has subsequently spread becoming a highly valued recreational resource.

1.3.6 Climate

The climate of the area is within the Sub-humid Transitional Low Boreal Ecoclimate Region (CCELC 1989). Winters are relatively cold while summers are relatively warm. Bissett (51° 1' N, 95° 42' W) is the most appropriate location for climatic observations. Unfortunately, climate monitoring at this station was discontinued in 1997. Historical average daily temperatures for Bissett are -19.5°C in January and 18.6°C in July. Average annual precipitation is 564.9 mm, of which 64 percent falls between May and September (Table 1).

Pinawa, located 57 km south of the study area (50° 10' N, 96° 3' W), is the nearest active meteorological station. Comparison of climatic averages for Pinawa and Bissett (Table 1, Table 2) indicates that these communities share a very similar climate. Bissett is approximately 1° C cooler annually and a greater proportion of precipitation falls as snowfall than the more southern Pinawa.

Table 1: Canadian Climate Normals 1968:1990 for Bissett

(Location 51°02'-N 95°41'-W, 268 m ASL). Data courtesy Environment Canada Source: Atmospheric Environment Service 1993. Canadian Climate normals. 1961-1990. Prairie Provinces. Environment Canada, Atmospheric Environment Service, Downsview Ontario.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Daily Maximum (°C)	-13.1	-8.4	-0.6	9.7	18.0	22.0	25.2	23.5	16.6	9.0	-1.4	-10.7	7.5
Daily Minimum (°C)	-26.0	-22.8	-14.8	-3.8	3.9	8.7	11.9	10.5	5.0	-0.3	-10	-22.1	-5.0
Daily Mean (°C)	-19.5	-15.5	-7.6	3	10.9	15.4	18.6	17	10.8	4.4	-5.7	-16.3	1.3
Rainfall (mm)	0.4	0.6	9.1	22.8	52.0	92.1	68.9	76.1	67.0	33.8	4.8	1.3	428.8
Snowfall (cm)	28.9	19.5	19.8	10.5	2.6	0.4	0	0	0.5	12.4	27.2	23.3	145.2
Total Precipitation (mm)	26.4	18.1	28.2	33.8	54.9	92.4	68.9	76.1	67.6	46.9	29.8	21.7	564.9

Table 2: Canadian Climate Normals 1971:2000 for Pinawa

(Location 51°02'-N 95°41'-W, 268 m ASL). Note: **1**. Pinawa is located 57km south of the study area. **2**. Data courtesy Environment Canada Source: http://www.climate.weatheroffice.ec.gc.ca/climate_normals/

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Daily Maximum (°C)	-12.6	-7.8	-0.4	9.7	18.1	22.2	24.8	23.7	17.3	9.8	-1.3	-9.8	7.8
Daily Minimum (°C)	-23.5	-19.5	-12	-2.9	4.7	10.1	12.9	11.6	6.3	0.4	-8.5	-19.0	-3.3
Daily Mean (°C)	-18.1	-13.7	-6.2	3.4	11.4	16.2	18.9	17.7	11.8	5.1	-4.9	-14.5	2.3
Rainfall (mm)	0.3	2	8.3	22	58.1	94.5	78.3	71.5	63.5	37.3	8.7	1.2	445.5
Snowfall (cm)	21.4	14.9	19.0	9.9	1.4	0	0	0	0.6	8.3	21.9	22.5	119.8
Total Precipitation (mm)	21.7	16.9	27.3	31.9	59.5	94.5	78.3	71.5	64.1	45.5	30.6	23.7	565.3

Observations in Pinawa from September 2003 to September 2004 indicate precipitation was 129.8 percent of normal over the 12-month period and approximately 20 percent higher than normal over the summer (Figure 2). The majority of the summer precipitation fell in May. Additionally the four-month period from May to August 2004 was on average 3.6 °C. cooler than normal (Figure 3). Climatic observations from October 2004 to October 2005 indicate that for the 12 month period precipitation was 126 percent of normal. June was an exceptionally wet month with precipitation 230 percent of the 30 year normal while the rest of the summer was drier than normal. On average temperatures in 2005 were 0.9 °C warmer than normal (Figure 2).

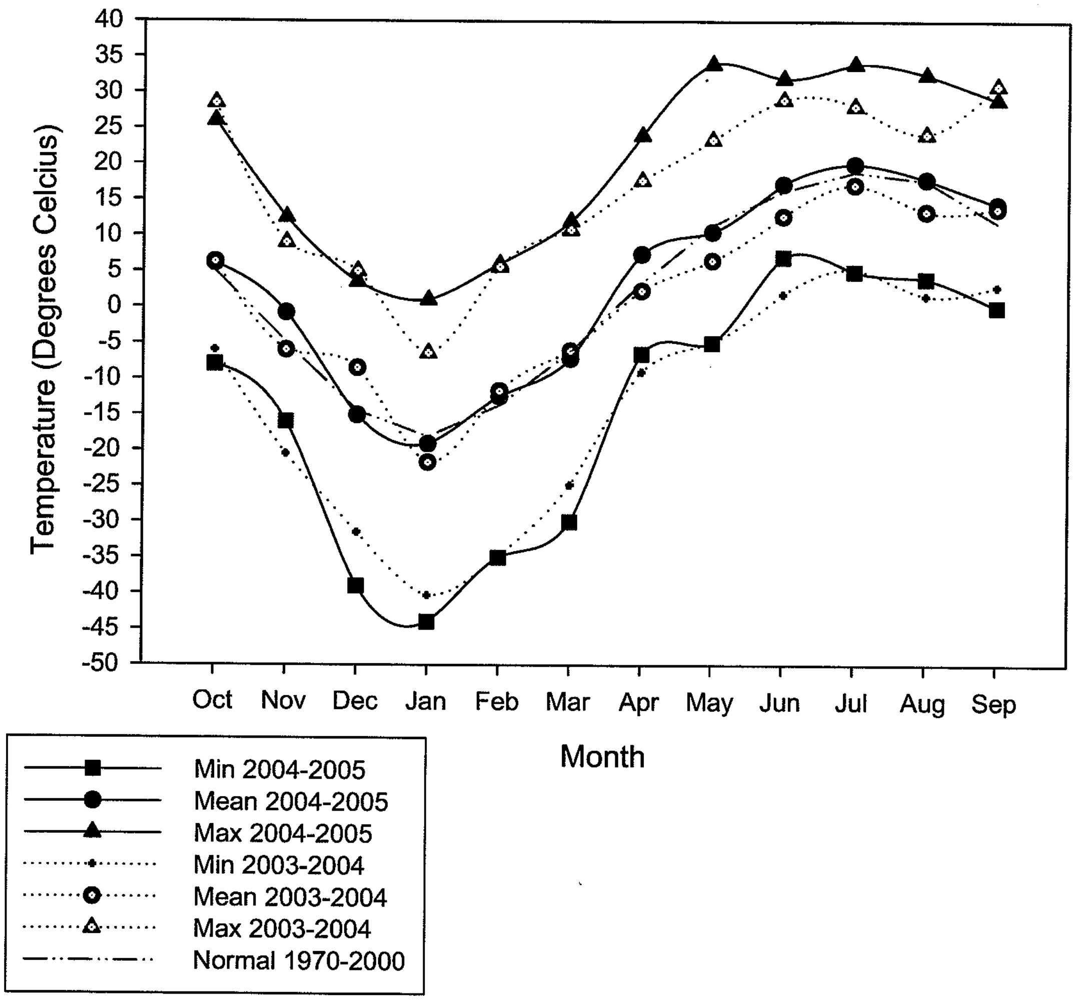

Figure 2: Mean, extreme minimum, and maximum temperatures for Pinawa between October 2003 to September 2005.

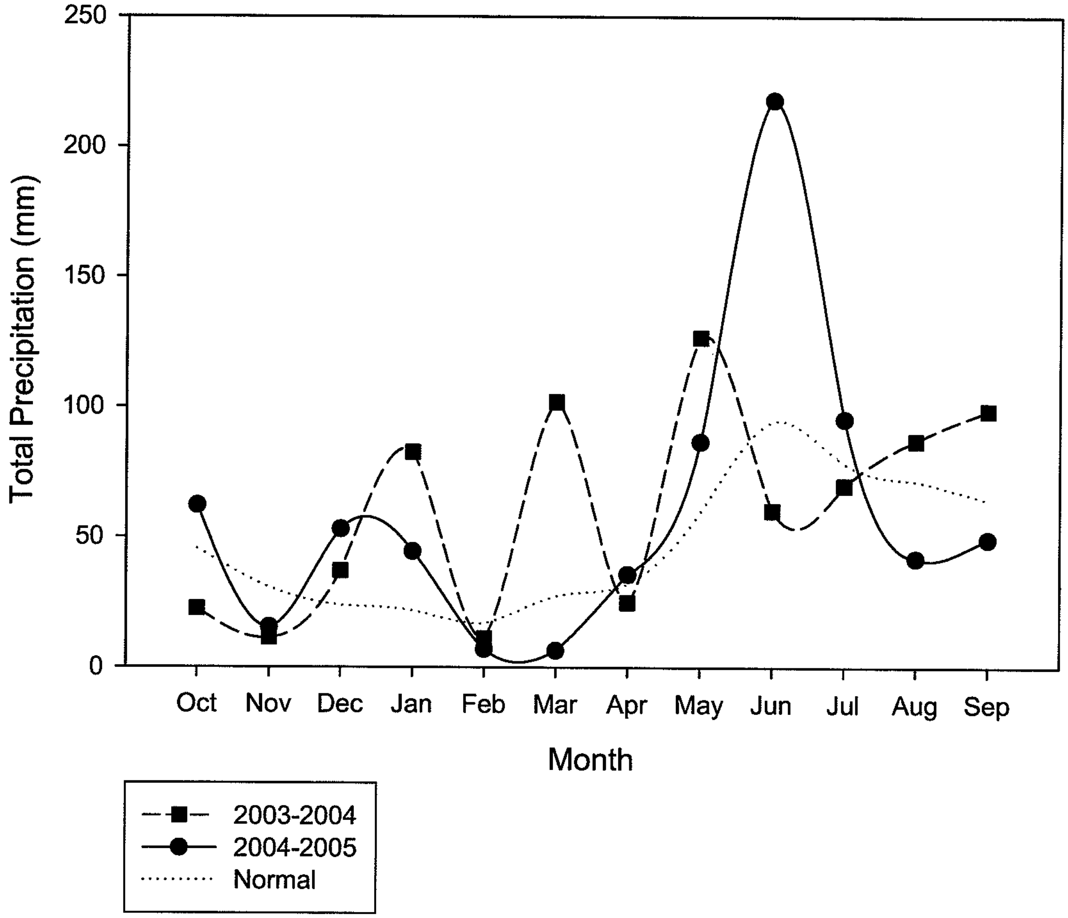

Figure 3: Mean and normal precipitation for Pinawa between October 2003 to September 2005.

1.3.7 Natural Disturbance

Natural watershed disturbance includes forest fire, damage by insects, forest disease, droughts, floods, and windstorm events. Fire is an important agent of natural disturbance and ecological process in the boreal forest. Historical data indicate that approximately 80 percent of the study area has burned at least once in the period between 1885 and 1989 (Ehnes 1998). Insect infestations and disease outbreaks can result in significant losses of merchantable timber, decreased property values and, in some cases, result in the decimation of a tree species. No evaluation on whether insect and disease outbreaks in a watershed have an impact on water quality has been conducted. The two most common insect pests in the study area are deciduous specific forest tent caterpillars (*Malacosoma disstria*) and the coniferous specific spruce budworm (*Choristoneura fumiferana*).

1.3.8 Recent and Historical Land Use

Archaeological research indicates that humans have occupied this region for at least 8000 years (Government of Manitoba 2001). Before 1800, Cree mostly occupied the area whereas today native communities are mostly the descendants of the Anishinabe (Saulteaux), a branch of the Ojibwa Nation, which migrated from the Sault Ste. Marie area of Ontario. Prior to European settlement, these people had a subsistence livelihood based on harvesting fish, game and the harvesting of wild rice. With European settlement in Canada and high demand for furs in Europe, by 1737 many aboriginal people became engaged in hunting and trapping for the lucrative fur trade.

By 1900, attention turned to the potential for timber harvesting, mineral exploration, and hydroelectric generation in the region. Hydroelectric generation began on the Winnipeg River to supply the expanding City of Winnipeg. In 1906 a hydroelectric station was constructed at Pinawa and in 1909 construction started on a station at Point du Bois. The 20th century saw the addition of four other generating stations on the Winnipeg River; while the Pinawa station was decommissioned in 1951.

In 1901 the J.D. McArthur Company operated a saw mill and brick yard at Lac du Bonnet (Rural Municipality of Lac du Bonnet, no date). Fuel wood and lumber were harvested from Seven Sisters north to the Bird River and shipped by rail to Winnipeg. Historical accounts indicate forest harvesting was extensive and utilized clear cut methods that were destructive to game stocks and the landscape, exhausting the wood supply by 1918 (Mochoruk 2004, p191). In 1926, McArthur and partner George Mead set up the Manitoba Paper Company and began construction of a pulp mill at what is now Pine Falls, Manitoba. This mill began operation in 1927 and is now the main destination for the region's harvested timber. The current owner is the Tembec Industries Inc. Pine Falls Operations.

Mineral exploration in the area began as early as 1896 when The Lac Du Bonnet Development Company formed to prospect for mineral rights. Prior to 1920, there was little development north of the Winnipeg River. In 1911, gold was discovered at Rice Lake, now the community of Bissett. This discovery sparked a boom in prospecting in the Wanipigow River area and in the region of what is now Nopiming Provincial Park. The two most successful mining operations occurred at the Central Manitoba Mine (north of Long Lake) from 1927-1937 and The San Antonio Mine at Bissett (1932-1985) (R.D Parker Collegiate no date). Other mine sites included the Gunner Mine (1936-1942), Ogama-Rockland Mine 1942-1951, The Jeep Mine

(1948-50), Gem Lake Mine (later the Diana Mine 1934-36) and the Solo-Oro Mine (1932-40). Further south at Bernic Lake an exploratory tin mine was set up in 1926 eventually discovering one of the world's largest reserves of cesium. Today this mine is operated by the Tantalum Mining Corporation and is a source of ores of lithium, cesium, tantalum, and spodumene. This and the recently reopened gold mine at Bissett (historically known as the San Antonio Gold Mine now operated by the Sangold Corporation) are currently the only active mines in the region. Despite this, the mining era opened up the region bringing with it a (limited) transportation network, electricity, and settlement that facilitated further recreational and economic development.

Today land use in the region is varied. Much of this area has no public roads, nor permanent settlements (for example, Atikaki Provincial Wilderness Park). The region offers extensive water based recreation opportunities with excellent canoeing and fishing. The region supports numerous fly-in fishing lodges and fishing out camps as well as a number of hunting outfitters. Cottage subdivisions are present at Bird Lake, Long Lake, Booster Lake, Davidson Lake, Beresford Lake, and Flanders Lake. Campgrounds exist at Bird Lake, Tulibi Lake, Black Lake, Wanipigow Lake, Wallace Lake, Tulabi Falls, Beresford Lake and Caribou Landing (Quesnel Lake). The area includes the communities of Manigotogan (population 192), Hollow Water First Nation (population 427), Black River First Nation (population 210), and Bissett (population ~100 though this fluxes with mining activity). There are no roads north of the Wanipigow River and no industrial resource development permitted inside Atikaki Provincial Wilderness Park however an all weather gravel road runs up the East Side of Lake Winnipeg just south of the Community of Bloodvein First Nation.

Forestry is still an important economic activity in the region. Extensive forest harvesting began in 1953 for the paper mill in Pine Falls (currently Tempec Industries Inc., Pine Falls Operations). Historically, trees were felled by chain saws and delimbed on site. This wood was hauled to a river to be stacked on the ice until spring thaw or delivered to a main haul road by horses or tractor. Advances in mechanization led to the use of mechanical fellers and skidders by 1980. Currently all pulpwood harvesting is mechanized. Forestry operations primarily target softwood coniferous species (jack pine, black spruce, and white spruce).

The majority of harvesting occurs during the winter which largely prevents extensive ground disturbance. Delimbing occurs on site. Logs are hauled by truck or chipped on site and hauled to Pine Falls. In accordance with provincial regulations, branches and other tree debris is spread in the harvest area. The aim is to ensure seed source and nutrients are retained for enhanced forest regeneration. Currently approximately 0.04 percent of the Forest Management Lease (FML) is harvested annually or 1200 ha/yr (Lidgett Inventory GIS Forester Tembec Industries Pine Falls Manitoba, pers. communication). Current forest harvesting is concentrated south of the Bloodvein River, with extensive harvest areas west of Happy Lake and in the Rainy Lake area east of Manigotogan Lake.

1.3.9 Future Land Use

Future land use in the region may include an expansion of cottage developments, a new permanent all weather road on the east side of Lake Winnipeg and possibly a major hydroelectric transmission line crossing what is now an undeveloped area. All of these activities have the potential to alter the landscape and may lead to the expansion of forestry, mining and resource based recreation activities in the region.

1.3.10 Current knowledge of lake water quality

Little is known about the status of water quality in the region. The provincial government conducted water quality assessments of a select number of lakes in the late 1970s. These were short term (1-2 years) and focused on lakes primarily with cottage subdivisions (Table 3). Most monitoring was restricted to south of the study area in Whiteshell Provincial Park. Water quality data, though sparse, are available for 20 lakes in Nopiming Provincial Park. Provincial records also indicate that data are available for 20 lakes in Whiteshell Provincial Park (Manitoba Conservation 2002). In addition, Macbeth (2004) conducted a water quality survey of 21 backcountry and 14 intensively used lakes in 2002 in Whiteshell Provincial Park. Within the study area, Jones et al. (1996) collected intensive data examining the effects of forestry herbicides on water quality in eight ponds. Limited bathymetric information is available for a number of lakes in the study area; typically, this is a reflection of recreational angling opportunities in accessible lakes. Fee et al. (1989) collected data on 115 lakes in the Red Lake district in 1985 and 1986. Though most of these lakes were in Northwestern Ontario, primarily in the vicinity of Woodland Caribou Provincial Park, 18 Manitoba lakes were sampled in 1985.

Approximately 150 km southeast of the study area, extensive data spanning a period from 1967 to the present are available for lakes in the Experimental Lakes Area of Ontario (N49° 34' to N49° 47' W93° 36' to W93° 52'). Water quality data are also available for Lake of the Woods (Ontario Ministry of Natural Resources unpublished data), and the Shoal Lake (City of Winnipeg Water and Waste Department unpublished data).

Differences in sampling techniques and methods of analysis used in each study make direct comparison of chemical data from different areas and periods difficult. Decadal or more gaps in data are common. Additionally, useful information regarding physical limnology is often missing. Comparable data are often missing, for example, provincial sampling in Manitoba for many years targeted only a specific parameter (chlorophyll *a)*. The region suffers from a lack of a consistent long-term monitoring program. With these limitations in mind, total phosphorus in lakes of the study region ranges from below detection limits to 3.20 mg/L. Median values for total phosphorus were 0.029 mg/L for Whiteshell Provincial Park (Manitoba Conservation 2002), 0.014 mg/L (Macbeth 2004), 0.023 mg/L for Nopiming Provincial Park (Manitoba Conservation 2002) and 0.019 mg/L for the Red Lake District (Fee et al. 1989). The Red Lake study measured dissolved and suspended nitrogen whereas the other three datasets measured total Kjeldahl Nitrogen and thus the data is not comparable between the Red Lake study and the other three datasets. However, total Kjeldahl nitrogen (TKN) observations for the three comparable datasets ranged from below detection limits (< 0.2 mg/L) to 25.2 mg/L for Whiteshell Provincial Park. Compared to lakes sampled in Nopiming Provincial Park, TKN concentrations appeared to be the highest in Whiteshell Provincial Park, though concentrations measured in the 2002 Whiteshell survey (Macbeth 2004) were all below 0.2mg/L. Outside the study area, mean total phosphorus concentrations for Shoal Lake Ontario, and Lake of the Woods fell into the range observed in the lakes within the study area (Table 4).

Table 3: Lakes with previous water quality data in the study area

Years indicate what years data is available for. Source: **(A)** Manitoba Conservation (2002), Water Quality Management Section. **(B)** Fee et al. (1989). Note: **(1)** * Sampled again in 2004, ** Sampled 2004 and 2005. **(2)** Latitude and

Lake name		Other name	Source	Latitude	Longitude	Year(s) sampled	Notes:
Manigotogan	*		A	50.8567	-95.6161	1976, 1977	
Long	*		A	50.8647	-95.4058	1976, 1977, 1982 - 1983	1982, 1983 only Chl a
Beresford	*		A	50.8669	-95.2336	1976, 1977, 1981 - 1983	1981- 1983 only Chl *a*
Flintstone	*		A	50.6944	-95.2858	1976, 1977	
Black	*		A	50.4047	-95.3408	1976, 1977	
Cat			A	50.6050	-95.4428	1976, 1977	
Euclid			A	50.5883	-95.3981	1976, 1977	
Bird	*		A	50.4669	-95.3658	1976, 1977, 1981 - 1983	1981- 1983 only Chl *a*
Booster	*		A	50.4481	-95.2711	1976, 1977, 1981- 1983	1981- 1983 only Chl *a*
Birse	*		A	50.4047	-95.3408	1976, 1977	
Bernic	*		A	50.8669	-95.2336	1977	
Davidson	*		A	50.4539	-95.1672	1994-1996	
Wanipigow	*		A	51.0964	-95.9708	1976, 1977, 1981-1983, 1992	1981- 1983 only Chl *a*
Quesnel	*		A	50.9172	-95.6289	1976, 1977	
Wallace	*		A	51.0128	-95.3647	1976, 1977, 1983	1983 only Chl *a*
Tooth	*		A	50.7475	-95.3247	1976, 1977	
Shoe	*		A	50.6600	-95.4664	1976, 1977	
Unnamed			A	50.6842	-95.4058	1976, 1977	
Springer	**		A	50.5325	-95.4517	1976, 1977	
Tulabi	*		A	50.4922	-95.2444	1976, 1977	
Fishing			B	52.1009	-95.4091	1985	
Mannifrank			B	51.8577	-95.2000	1985	
Dogskin	*		B	51.7116	-95.2001	1985	

Table 4: Summary of historic water quality in and near the study region

Note: Nopiming Provincial Park, Ponds along Highway 304 and some sample sites in the Red Lake District were in the study area. **1.** ND = data not available. 2. **Sources: (A)** Manitoba Conservation, Water Quality Management Section (2002), **(B)** Macbeth (2004), **(C)** Fee et al (1989), **(D)** Jones et al. (1996) **(E)** Ontario Ministry of Natural Resources, Ontario Lake Keepers Program (unpublished data), **(F)** City of Winnipeg, Department of Water and Waste (unpublished data)

Region	**Source:**	**Number**	**Sampled**	**Total Kjeldahl Nitrogen** mg/L			**Total Nitrogen** mg/L			**Total Phosphorus** mg/L			**Chlorophyll *a*** mg/L		
				mean	min	max	mean	min	max	mean	min	max	mean	min	max
Whiteshell Provincial Park	A	20	1963-1999	700	<200	25200	ND	ND	ND	40	<1	3200	11	<1.0	910
Whiteshell	B	35	July 2002	<200	<200	400	ND	ND	ND	20	10	80	ND	ND	ND
Nopiming Provincial Park	A	20	1976-1996	540	230	1100	ND	ND	ND	30	<20	100	5	<1.0	25
Red Lake District	C	115	1985	ND	ND	ND	530	200	1380	20	10	40	5	1	17
Ponds along Manitoba Provincial Highway 304	D	6	1985-1993	990	500	2300	ND	ND	ND	30	1	250	10	2	52
Lake of the Woods, Ontario	E	1	2005	ND	ND	ND	ND	ND	ND	20	10	90	ND	ND	ND
Shoal Lake, Ontario	F	1	2004	460	310	630	ND	ND	ND	10	10	20	6	3	17

2.0 Literature Review

2.1 Introduction

Approximately 400 000 hectares of forest are harvested annually in the Boreal Shield (Environment Canada 2000). Harvesting practices are currently modeled after natural disturbance patterns (Hunter 1993; Franklin 1993). The premise is that if harvesting patterns imitate fire, ecosystem integrity will be maintained. This remains largely unverified for both terrestrial and aquatic ecosystems (Carignan et al. 2000). If forest management is to emulate natural disturbance, the effects of both fire and forestry must be understood (Tonn et al 2003). This is essential in promoting environmental and financial sustainability (Reeves and Rosen 2002).

The majority of research into effects of forestry on water quality has focused on the stream ecosystems while a limited amount has focused on lakes (Rask et al. 1993, Rask et al. 1998, Carignan et al. 2000, Pinel-Alloul et al. 2002). Of studies conducted on lakes, the majority have been short term while very few have examined the longevity of impacts or the effects of repeat disturbance. Much of the literature is contradictory. For example, nitrogen and phosphorus concentrations were observed to increase, or remain constant and these changes may be long or short term. This is likely a testament to the tremendous size, climatic, topographic and geologic variability of the boreal region. In general, the magnitude of the effects observed are proportional to the size and severity of the disturbance measured as a percentage of the catchment disturbed. The forestry activities most likely to affect water quality include road construction and use, timber harvesting, forest regeneration, site preparation and application of forest chemicals

(Jewett 1996). The use of cumulative annual percentage watershed harvest may not be a good single indicator of sediment yield increase. Instead, the ratio of lake volume to watershed area of forest harvesting can be used as an index of sensitivity to watershed harvesting. Watersheds with higher drainage ratios would be more sensitive to watershed disturbance. For example water quality in lakes with drainage ratios of 2-3 (Steedman 2000, Scully et al. 2000) were less sensitive to forest harvest than watersheds with drainage ratios of 2-15 (Carignan et al. 2000). The development of an impact statistic, incorporating important factors such as drainage area, stream density, road density, area harvested, lake surface area, and watershed slope may provide a single number that can be used as a more powerful predictor of the effects of harvesting practices than use of watershed area harvested alone (Pettigrew et al. 1999). This review attempts to highlight the physical, chemical and biological effects on water quality resulting from fire and harvest disturbance.

2.2 Physical Effects

The magnitude of the physical effects observed on lake water quality from watershed disturbance is typically a function of lake volume and catchment size. Large catchments draining into small, shallow lakes are expected to show the greatest rate and degree of change (i.e. lakes with short mean residence times). Lakes, as opposed to streams, experience the effects of watershed disturbance over a longer time scale and may take years to reach equilibrium (Smith et al. 2003). Areas with a high watershed to lake area/volume ratio generally show the fastest response to impacts. However, lakes with smaller drainage ratios may be more sensitive to influences other than watershed disturbances e.g. atmospheric pollution or climate change

(Paterson et al. 2002).

Severity of changes will be dependent upon basin morphology, lake volume and perimeter to area relationships. The response to forest practices depends strongly on site and weather conditions, making extrapolation of effects across different regions very difficult (Binkley and Brown 1993). Typically, on a watershed area basis, logging occurs on a smaller proportion of the watershed than forest fires. This may account for some of the differences observed in harvested watersheds versus burned watersheds. The type and intensity of fire is another variable in the literature. For example, crown fires may leave the understory relatively undisturbed, maintaining the stability of soils in the watershed (Johnson 1992 quoted in Paterson et al. 2002), whereas other fires may burn to the ground, leaving soil exposed to erosion.

2.2.1 Erosion and water yield

Removal of vegetation reduces evapotranspiration and increases water yield (Martin et al. 2000; Swank et al. 2001; Prepas et al. 2003). Greater exposure of soil to erosion and weathering is possible (Singh and Kalra 1977). In addition, ground water infiltration is reduced which may lead to increased transport of organic matter and soluble mineral constituents. In the Canadian Shield, microbial activity may result in an increased concentration of sulphate ions, reducing pH (Krause, 1982). Forestry operations have the potential through soil disturbance, road building or harvesting to cause large quantities of sediment to enter watercourses, resulting in increased turbidity and siltation (Beaty 1994, Nisbet 2001). The risk of sedimentation is particularly great where the soil is erodible and operations are followed by a period of very wet weather (Nisbet 2001). Aeolian transport of sediment is an important geomorphic process in many areas of the world. Steedman and France (2000) provide evidence of how windblown sediment from an upland harvested area in Northwestern Ontario Cold can be transported into lakes. Soil may be transported by wind, particularly under dry conditions, a factor most evident with forestry roads although limited to a radius of about 10 m around the road (Steedman and France 2000). In this study, though sedimentation of lakeshore habitat was above background rates it was of short duration (1-2 years following disturbance) and unlikely to cause any significant alterations in water quality or habitat for fish, algae or invertebrates in the study lakes.

Forest removal will reduce litterfall and increase splash erosion (France 1997, France et al 1998), soil transport and DOC export to streams and lakes (Beaty 1994). Clearcutting leads to a decrease in interception and transpiration of precipitation, increasing soil moisture, raising the water table and increasing stream-flow (Ramberg 1976). Swank et al (2001) noticed a 28 percent increase from expected baseline stream flow in watershed clear-cut experiments in North Carolina. Prepas et al. (2003) found similar results in a fire-affected system in Alberta. Alterations to stream flow volume can lead, in turn, to increased water flow into lakes (Verry et al. 1983, Buttle and Metcalfe 2000). However, observed changes may or may not be consistent over the entire season. Wynn et al. (2000) found in the coastal forest of Virginia that, while overall stream water yield increased following forest harvesting, dry season yield decreased. The duration of these changes were limited by the re-establishment of site vegetation (Sun et al. 2000). Groundwater chemistry may be affected by logging through increased availability of surface water and washing of mobile ions through the soil profile into groundwater (Bari et al. 1996). Forest harvesting can alter infiltration and percolation processes by compacting the soil and removing the duff layer (Nip 1991). The increase in surface water, as mentioned previously, can lead to increased seepage and transport of soil constituents in the ground water; however, if changes to the ground water system are realized, they may be subtle and or take years to be observed (Reeves and Rosen 2002). It has been hypothesized that increased stream water yield may increase lake levels and affect the timing of maximum spring lake levels (Miller 1996). This would be most evident in shallow lakes with large catchments and constricted outlets. Results from the Tri-Creeks Experimental Watershed in Alberta indicated total snow accumulation was greater in cut blocks than in adjacent residual forest (Nip 1991). This increased moisture availability could be a potential erosion agent during the spring melt.

Heavy equipment can damage soil through compaction, rutting and ditching operations. Erosion becomes dependent in part upon the extent to which soil has been damaged by heavy machinery, logging roads and drainage ditches (Ramberg 1976). Both road construction and timber harvesting will increase sediment loads to both streams and downstream lakes; however, road construction has the most dramatic effect (Krause 1982; Nip 1991; Nisbet 2001; Cornish 2001). In the Tri-Creeks Watershed study of Alberta, stream crossings access roads and crossing of ephemeral draws were the prime source of sediment entering streams. Sediment load increased in both buffered and unbuffered cut blocks (Nip 1991).

Mechanical site preparation is often an important process needed for forest renewal in silviculture applications. Mechanical site preparation may create a potential for increased soil erosion and stream sedimentation (Krause 1982). This is not restricted to creeks, as Rask et al. (1998) found soil scarification to be a major cause of limnological changes in a small Finnish lake. Soil scarification between 15-30 percent of a watershed was identified as a major influence changing water quality in three lakes (Rask et al. 1998). Nutrient concentrations, pH and alkalinity increased after soil scarification. Mechanical site preparation utilized on Tembec's forest management lease includes drag chains, barrels, disk trenching, and shear blading. Disk trenching and shear blading cause the greatest disturbance to soil and are typically used to regenerate a black spruce dominated forest. Drag chains have been found effective as a means of seed dispersal in what was formerly jack pine dominated stands.

It is thought erosion can be mitigated by proper streamside management zones (i.e. buffers) (Kochenderfer and Edwards, 1991). However, erosion may be greatest, long after completion of harvesting operations. In areas with considerable relief such as the Rocky Mountains, the decay of tree roots can lead to mass movement of soils long after completion of harvesting. The extent of erosion is likely highly dependent upon the soils type, relief, re-vegetation rates and climatic conditions. For example bedrock soil would be less prone to erosion than a clay type soil.

2.2.2 Effects on temperature

Increased water temperature (Steedman et al. 2001) is an expected effect of forest clearing. Increased water temperature is a common response due to clear-cutting, both in lake and flowing water systems due to less shade offered by the forest canopy (Krause 1982). In harvesting experiments in the Severn Uplands of Northwestern Ontario, Nicolson (1975) found average daily maximum stream water temperature increased from 14°C to 19°C during the April to October field season. Johnson and Jones (2000) found June diurnal fluctuations in stream water temperature increased from approximately 2°C to 8°C in a clear-cut Oregon catchment.

2.2.3 Effects on stratification

Decreases to stream and lakeside vegetation can increase wind velocity, decrease thermocline depth and increase epilimnetic temperature. Furthermore, removal of forest cover may lead to increases in wind exposure and decrease the clarity of lakes. This can change thermal stratification, mixing and dissolved oxygen regimes. Rask et al. (1993) found silvicultural treatments altered the autumnal turnover from a pre-treatment depth of 5 to 6 meters to the entire water column in a Finnish Lake (maximum depth 11 metres, average depth 8 metres). A reduction in the thickness of the oxygenated layer from 3.5-4.5 metres to 2.5 metres following clear cutting to 1m following burning of logging waste also occurred. This indicated increased biological oxygen demand. In another study, Rask et al. (1998) found that following forest harvesting in Finland, the mixing regime of some previously un-mixed meromictic lakes became mictic. Decreased wind protection was believed to be the cause. Steedman (2000) found a 1 metre decline in thermocline depth following partial harvesting of watersheds in Ontario.

2.3 Chemical effects

The impacts of forest disturbance on water quality are highly variable and often contradictory. There is a danger in extrapolation from one area to another. Differences in climate (e.g. coastal forests with high precipitation versus the drier forest of Alberta), watershed to lake area ratios, geology (e.g. nutrient poor bed rock soils versus nutrient rich glacial till), forest type (e.g. hardwoods versus softwoods), and topography can account for some of these differences. The type of harvest management activities used including site preparation, buffer size and number of stream crossings further compounds analysis.

The effects of forest fire and harvesting on water quality, though similar, are not the same (Lamontagne et al. 2000). Forest fire tends to remove a larger area of the catchment than forest harvesting such that effects of the two may not be directly comparable. In harvested systems, increases of litter decay subsequently lead to increased nutrient release. Fire typically mineralises

the organic soil layer, releasing nutrients which may be leached from the watershed to the lake or enter directly in the form of windblown ash. Fire mineralises nutrients to their inorganic form which may be transported into water bodies, whereas forest harvesting typically leaves the organic soil layer intact. Schindler et al. (1980) suggests that catchment deforestation by wildfire is not likely to cause important water quality changes in Precambrian
Shield lakes unless water renewal time is short, relative to the time required for catchment revegetation. Studies at Hubbard Brook Experimental Watershed have demonstrated that nitrate, sodium, calcium, and magnesium export can increase following harvesting (Likens et al. 1970). Increases in light, heat, moisture, and soil organisms increases decomposition of organic matter and soil mineralization (Bormann and Likens 1979; Hornbeck et al. 1986; Johnson 1995; Martin et al. 2000). This can lead to nitrification and production of nitric acid in the forest floor and soil (Likens et al. 1970; Bormann and Likens 1979; Dahlgren and Driscoll 1994). Nitric acid production acidifies the soil by cation exchange and mobilizes base cations (calcium, magnesium, sodium, potassium) and aluminum. Base cations bind with nitrate and can be leached from soils to stream water (Likens et al. 1970; Dahlgren and Driscoll 1994). Multiple fires in the same watershed may have a decreasing affect on water quality. For example depending on the intensity of the fire, if the entire soil and duff layer are burned there will be less erodable material remaining in the watershed to be transported into lakes with subsequent fires.

It is conceivable that increased stream water concentrations of base cations and nitrate would have downstream effects on lakes. Lamontagne et al. (2000) found the increases in cumulative losses of base cations, though total nitrogen and total phosphorus exports were similar between harvested and burned watersheds; however, harvested systems exported more organic compounds while burned systems exported more inorganic compounds (magnesium, nitrate, and sulphate). Vouri et al. (1998) found forest drainage through ditching operations significantly altered the chemistry and negatively affected the benthic biodiversity of Finnish head water streams. In particular, pH and alkalinity were lower in streams affected by drainage while suspended solids, colour, iron and aluminium concentrations all increased with ditching operations.

Through reduced evapotranspiration of the forest, clear cutting and forest fire are expected to increase the leaching of ions out of the soil but the extent and type depends on the properties of underlying soils (Krause 1982). Key limnological characteristics are likely influenced by catchment and morphometric properties such as the drainage ratio (DR), mean residence time, and watershed slope (Schindler 1971; Engstrom 1987; Rasmussen et al. 1989, Carrignan et al. 2000). Water quality in lakes with a high mean residence time would experience a greater dilution of changes to inflowing water over time versus shallow lakes with a short mean residence time and faster water movement. That is, the water quality in quickly renewed lakes would become more similar to inflowing tributaries more rapidly than lakes with a long residence time. Drainage ratio (the ratio of watershed area to lake area) and watershed slope are both indicators of water movement. Lakes with a high drainage ratio (DR) and watershed slope are expected to experience more rapid movement of water from a watershed than lakes with a low DR and little watershed relief.

The effect of watershed disturbance on water quality is likely related to the properties of the soils in question. For example, Prepas et al. (2001) found that in the nutrient rich Boreal Plain of Alberta, a 15 percent watershed disturbance had a noticeable effect on the water quality. Carignan et al. (2000) found it took a 30 percent level of disturbance of nutrient poor rocky Quebec watersheds to have a similar effect.

2.3.1 pH

Clear cutting in coniferous forests can lead to increased concentration of dissolved organic substances and lowering of the pH of stream water. Nicolson (1975) found pH decreased in the first year following clear cutting from an average of 5.76 to 4.97; however, it increased to 5.22 in the second year. Streams were enriched in ammonia, dissolved organic nitrogen and phosphorus, although nitrate concentrations decreased where clear-cutting had occurred. On the other hand, Rhodes and Davis (1995) and Korhola et al. (1996) reported an increase of about one pH unit after fire. Åstrom et al. (2001) found stream pH increased approximately one unit following ditching operations in Finland. Manganese, calcium, magnesium and aluminum concentrations also increased. Increases in pH may have been attributable to loss of base cations (calcium, magnesium) from the watershed to stream and lake water. Decreases in pH may have been attributable to oxidation of soil organic matter and nitrification by soil bacteria.

Enach and Prairie (2000) using a paleolimnological approach inferred that historical pH changes after fire within Lac Francis (western Quebec) may either increase or decrease by an order of magnitude (0.5-1 units). Consequently, predictions of pH changes after disturbance seem unreliable at best. It is conceivable that the presence of alkaline ash in burned systems may increase pH.

The response in lakes from deforestation may be delayed or reduced because of the dilution of runoff in lake volume (Carignan and Steedman 2000). In general, forest harvesting and fire leads to increases in dissolved organic carbon (DOC), phosphorus and nitrogen concentrations in lake systems. DOC increases are more prominent in cut systems and fire generally produces more nitrate than harvesting (Carignan and Steedman 2000).

2.3.2 Dissolved Organic Carbon

Dissolved organic carbon (DOC) is one of the key determinants of the ecology of Boreal Shield lakes (Schindler et al. 1992, 1997). Dissolved organic carbon is responsible for giving lake water a brown-tea like appearance. The primary source of DOC derived from the drainage basin of a lake is often wetlands (peatlands, bogs and fens). DOC participates in the transport (Bayley et al. 1992; Allan et al. 1993) and cycling of nutrients in Shield lakes (Schindler et al. 1992). Terrestrial DOC imports to Boreal Shield waters and determine optical properties such as the light extinction coefficient (Fee et al. 1996). DOC can influence light extinction in lakes and therefore water temperature, and thermocline depth in Shield lakes less than 500 hectares (Fee et al. 1996). Higher DOC in harvested systems increase light extinction coefficients (Lamontagne et al 2000). DOC export can transport contaminants such as mercury into lakes (Garcia and Carignan 1999). Photo degradation of these contaminants would also be reduced by increased light extinction.

France et al. (2000) examined DOC concentrations in 116 boreal lakes on the Canadian shield in Quebec (Lehmann 1994), and Ontario (Steedman 1999; France et al. 1999) and found that dissolved organic carbon concentrations in these lakes were affected by harvesting and wildfire; however, the direction and extent of this change was related to topography, percentage wetlands in the watershed and extent of the landscape disturbance. A high watershed to lake area contributed to increases in DOC observed. Logging in these lakes was often disproportionably focused on watersheds with a high proportion of wetlands; given this DOC was likely high in these lakes prior to watershed harvesting (France et al. 2000). Allen et al. (2003) describes the relationship between higher DOC (i.e., humic substances) and greater input of allochthonous substances in coniferous watersheds than in the deciduous-dominated Mixedwood Ecoregion of Alberta. Considering this factor, the type of forest disturbed would have a role in any resulting chemical changes.

Lamontagne et al. (2000) hypothesized that increases in DOC export rates will be the highest where soils experience seasonal water saturation and when harvested areas occur on saturated soils. Should this hold true, this is an important observation for harvest management in that harvesting should be minimized in wet areas and sensitive times of the year (i.e., spring) to minimize DOC export.

DOC increases of between 10-40 percent were likely responsible for 25 percent reduction in light penetration in lakes with experimentally harvested watersheds near Thunder Bay, Ontario (Steedman 2000, Steedman and Kushneriuk 2000). However, in Quebec, Carignan et al. (2000) found that, while DOC concentrations did not differ significantly between burned and reference lakes, cut lakes had significantly higher DOC concentrations than reference lakes. DOC and the coefficient of light extinction in burned lakes increased significantly over time, approaching those of the cut lakes three years after disturbance. DOC concentrations seem to be regulated by local topography. Increased DOC concentrations in harvested systems may be attributed to the fact that logging generally is disproportionately centred on watersheds of low relief and large surface area relative to that of their associated lakes. These watersheds usually also contain a high proportion of wetlands which contribute to DOC. In burned systems, it is also conceivable that much of the duff layer of the soil is volatilised, becoming unavailable for export. Although increased DOC concentrations are likely to be observed, light conditions particularly for small lakes and streams might improve because of reduced shading. This could possibly increase primary productivity (Ramberg 1976). In Quebec lakes Carignan et al. (2000)

found DOC increases can influence other key limnological properties. For example, in small lakes reduced water clarity reduces mixing depth and the depth of the euphotic zone where photosynthesis can occur (Fee et al. 1996).

Tonn et al. (2003) found that burning had the greatest impact on water quality in lakes of the Alberta Boreal Plain. Colour and total phosphorus concentrations were the highest in burned lakes when compared to reference and harvested lakes whereas pH, alkalinity, calcium were all lowest in lakes with burned catchments.

2.3.3 Nitrogen and Phosphorus

Phosphorus load is typically the main determinant of primary productivity in Boreal Shield lakes and the N:P ratio can influence the composition of algal populations (Schindler 1977). Forest harvesting can increase water yield, decomposition of the litter and weathering of soils. Typically, intact forests retain phosphorus. Decreasing phosphorus uptake by plants increases phosphorus in the soil water, consequently, increased runoff could increase phosphorus export to water bodies (Evans et al. 2000). Thus, loss of vegetation increases phosphorus export. Transport of nutrients following disturbance may be highly dependent on precipitation (Rask et al. 1993). High precipitation years would lead to increased water movement and increased transportation of nutrients and DOC from the watershed to receiving lakes and streams.

In the Severn Uplands of north western Ontario, Nicolson et al. (1982) found total phosphorus yield doubled the first year after harvest and remained at three times above the control four years after harvesting disturbance in a stream ecosystem. Prepas et al. (2002) found phosphorus export in burned watersheds exceeded that of a reference watershed by seven times in the Boreal Plain of Alberta. In Canadian shield lakes of Quebec, Lamontagne et al. (2000)

described increases in TN and TP loading of 33 percent and 64 percent respectively in lakes with burned basins and of 41 and 58 percent respectively in lakes in harvested basins. Carignan et al. (2000) studied the same lakes as Lamontagne et al. (2000) and found nutrient pulses in lakes following forest fires in the boreal region. Yearly average phosphorus concentrations were significantly higher in lakes with cut and burned watersheds than reference lakes. Aside from the lakes with harvested watersheds, concentrations were the highest in the spring and declined by approximately 20 percent in reference lakes and up to 50 percent in some burned lakes through the summer.

McEachern et al. (2002) found that in the Caribou Mountains of northern Alberta subarctic boreal lakes with burned catchments showed on average a three fold increase in total phosphorus, a five fold increase in total reactive phosphorus and a one to two fold increase in total nitrogen concentrations relative to unburned reference lakes. Between 20 to 95 percent of the catchment areas were burned. Colour was two to three times higher in the burned versus unburned catchments. Enache and Prairie (2000) found similar results using a paleolimnological approach examining the diatom community in the sediments of Lac Farncis Quebec. Their study determined that while DOC and pH changed little following fire disturbance, phosphorus concentrations increased up to two fold.

When examining stream systems affected by forest fire in Glacier National Park, USA Spencer et al. (2003) found that stream phosphate, nitrate, and ammonium concentrations increased by a factor of five to 60 over reference concentrations. High nitrogen concentrations were attributed to diffusion of smoke containing high nitrogen concentrations into the stream water, while phosphate increases were attributed to dispersion and deposition of ash into the streams. While nutrients returned to near background concentrations within several weeks after fire, there were episodic nutrient increases, correlated to spring run off events. Smoke and ash can transport significant amounts of nutrients, leading to eutrophication of lakes and streams (Spencer et al 2003). In regard to fire suppression, while a return to more natural fire cycles may be ecologically desirable, the increased nutrient release into streams associated with smoke and ash from fires in Glacier National Park may run counter to the goals of years of nutrient management activities in sensitive watersheds.

Peatland seems to play an important role with respect to elevated phosphorus concentrations in lakes with catchments that burned over the past three decades in Northern Alberta (McEachern et al 2000). While in the eastern boreal forest of Ontario and Quebec, phosphorus is generally the nutrient most limiting to growth (Schindler 1974), the western boreal forest of Canada is generally fertile but N-deficient (McEachern et al 2002). In this region, cyanobacteria blooms are common, high winter oxygen depletion and poor water quality has been noted (Riley and Prepas 1984). This area is thought to be highly sensitive to eutrophication following catchment disturbance, an expectation less evident in areas with underlying granitic rock and poorly developed soils such as the eastern Boreal Shield.

Nitrification normally occurs at clear cuttings (Ramberg 1976). Kochenderfer and Edwards (1991) witnessed increase nitrification with forest harvesting in New England. They hypothesised that this was a result of decreased plant uptake, increased water outflows, and increased soil temperatures, all of which lead to higher rates of mineralization and nitrification. However, Lamontagne et al. (2000) found none or very little nitrate loading following forest removal in the Canadian Shield of Quebec. Carignan et al. (2000) observed nitrogen behaviour differed substantially between lakes harvested and burned. While nitrate was generally low (often below the detection limit) in harvested and reference lakes, very high spring concentrations were measured in two out of nine burned lakes, three out of nine burned lakes had intermediate nitrate concentrations and four out of nine had concentrations that did not exceed reference concentrations. Total nitrogen was the highest in burned lakes followed by cut lakes. In addition to the external nutrient transport, internal nutrient loading from the sediments may be an important factor in shallow unstratified lakes. Rask et al (1993) describes how increased mixing of a Finnish lake due to removal of shoreline vegetation increased the availability of nutrients in the water column (particularly nitrogen).

2.3.4 Dissolved Oxygen

Generally, increased nutrient supply, DOC and sediment load will trigger respiration by micro organisms and increase oxygen depletion in the hypolimnion. In addition, changes to primary productivity will increase biological oxygen demand particularly during the winter months (through decomposition of algal biomass). Lakes with a small hypolimnion relative to their volume are usually the most sensitive to hypolimnetic oxygen depletion (McNamee et al. 1987). Oxygen depletion can change the redox potential of the sediments, releasing phosphorus and contributing to cyanobacteria blooms (Rask et al 1998).

2.3.5 Major ions

Trends in major ions resulting from forest disturbance can be hampered by interannual precipitation patterns. For example, in Quebec reference lakes, sulphate decreased by seven percent while sodium increased by six percent (Carignan et al. 2000). Potassium and chloride concentrations were much higher in cut and burned lakes. This relationship was directly proportional to the amount of forest cleared. On the other hand, calcium and magnesium concentrations were between two to four times higher in the burned lakes than harvested or reference lakes.

2.3.6 Metals

Humic substances can transport mercury from the catchment into lake waters and sediments. These can also cause both abiotic mercury methlyation and accelerate microbial methylation (Rask et al. 1998). Forestry operations increase concentrations of humic substances and possibly mercury. This may be accelerated by mechanical site preparation i.e. tilling the soil for forest regeneration (Porvari et al. 2003).

In a Finnish lake, Rask et al (1998) found that while mercury concentrations in perch (*Perca fluviatilis)* of >1 mg/kg (ww) were high, these concentrations decreased following clearcutting and soil scarification. The reason for this is unclear although it most likely relates to changes in water quality affecting mercury dynamics in the ecosystem. High DOC loads from harvested watersheds lakes are associated with high methyl mercury in zooplankton and fish (Garcia and Carignan 1999, 2000, Carigan et al. 2000).

In Northern Pike (*Esox lucius*) of 20 Quebec lakes, average mercury concentrations in 560 mm pike were significantly higher in lakes with watershed logging (3.4 mg·g–1 dry weight), than in reference lakes (1.9 $mg \cdot g^{-1}$) (Garcia and Carignan 2000). However, concentrations in lakes with burned watersheds (3.0 $mg \cdot g^{-1}$) were not significantly different from reference lakes or lakes with harvested watersheds. In all logged lakes, mercury concentrations exceeded the World Health Organization's safe consumption limit of 0.5 mg·g wet weight^{-1}. Mercury concentration in northern pike paralleled increasing DOC loading and lake water sulphate concentrations and declined with increasing pH. If forestry practices increase dissolved organic carbon loading and subsequently mercury concentrations in fish this might have important implications for forestry management decisions. In Finland significant increases in the runoff output of total mercury and methyl mercury from a small Finnish catchment after clear-cutting and soil scarification were also observed (Porvari et al. 2003). The export of mercury in this study appeared to be longer lasting than other parameters e.g. DOC. In addition, higher methyl mercury concentrations were recorded in the second and third year after logging, thus suggesting a longer lasting effect on the output of methyl mercury than on total mercury (Porvari et al. 2003). Allen et al. (2005) investigated whether forest fires in Alberta had an impact on mercury concentrations in macro-invertebrates and fish from lakes with burned and un-burned catchments. Two years after fire disturbance, concentrations were similar among lakes with reference and burned watersheds. Watershed fire did not increase concentrations of MeHg. To the contrary, in a pre and post fire experiment, the methyl mercury concentration in one lake was observed to decrease 11 fold from the previous year. This dilution of methyl mercury concentrations was attributed to increased primary production in the lake, caused by nutrient mineralization and enrichment resulting from the forest fire. The limited understanding of mercury dynamics in lakes with harvested and burned watersheds is an item of concern, particularly in areas with intensive forestry, and merits further study. Iron export may increase with silviculture operations. Vouri et al. (1998) found high iron concentrations resulting from forest drainage in Finland have the potential to adversely affect macroinvertebrates and fish either through iron precipitates or direct toxic effects. High iron concentrations were found to negatively affect habitat quality and correlated with reduced benthic biodiversity.

2.4 Biotic effects

Typically, quantification of biological impacts of watershed disturbance has fallen behind chemical and physical impacts (Carignan and Steedman 2000). Odum (1969, 1985) proposes that following disturbance there is a shift from larger to smaller organisms due to the greater ability of smaller organisms to colonize newly created and changing habitats.

2.4.1 Effect on macrophytes

Reduced water clarity resulting from increases in DOC and suspended sediment can reduce the size of the photic depth. Vegetation near the limit of the photic depth in the deepest waters is most likely to be affected (McNamee et al. 1987). Increased dissolved organic carbon may limit production of submerged aquatic plants (Pinel-Alloul et al. 1998).

2.4.2 Effect on phytoplankton and primary productivity

Rask et al. (1993) found that the phytoplankton community changed significantly in lakes with harvested watersheds from a domination by chlorophytes and chrysophytes to that of diatoms and blue-green algae by the end of the five year study period. Phytoplankton biomass was also observed to increase from 10 to >20mg/m^3, indicating eutrophication of the lake.

In a Quebec study, significant impacts on species richness of planktonic communities were not observed except in lakes that had large drainage basins with greater than 40 percent of the watershed area disturbed (Pinel-Alloul et al. 2002). In lakes with burned watersheds, increases in chlorophyll *a* concentration were observed. Diatoms, rotifers and large crustaceans showed sharp increases in these burned watersheds. In lakes with watershed harvest, nutrient enrichment did not trigger proportional increase in plankton production due to increased DOC concentration and increased light attenuation. Paterson et al. (1998) did not find apparent limnological changes resulting from watershed fire in Northwestern Ontario lakes, as determined through an examination of chrysophyte populations in sediment cores. Paterson et al. (1998) inferred that clear-cutting and wildfire have had little effect on these study lakes, despite removal of over 90 percent of the forest in some of the disturbed watersheds.

In a survey of 20 lakes with burned and unburned catchments in northern Alberta, McEachern et al. (2002) found that pelagic chlorophyll concentrations appeared to be unaltered. However, phytoplankton species richness declined by 36 percent for the 10 lakes with watershed fire. On the other hand, Nicholls et al. (2003) found the number of phytoplankton taxa decreased in two of three treatment lakes although large changes in water chemistry were not detected (Steedman 2000). Post fire light penetration decreased, which probably reduced phytoplankton diversity. Nicholls et al. (2003) conclude that this was related to decreased nitrogen to phosphorous ratio (a reduction in the ratio of N:P leading to nitrogen limitation and light limitation). The observed switch in community composition from *Anabaena* to *Aphanizomenon* genera of algae is consistent with this trend (McEachern et al 2002). In Finland, Rask (1993) noted periphyton biomass increased between two to four fold in lakes with experimental watersheds forest harvesting and soil scarification. A cyanobacteria bloom in one lake indicated a possible eutrophication, however, soil scarification appeared to be the major cause of limnological changes. In a later study, Rask et al. (1998) found no clear responses in phytoplankton after catchment forestry in three Finnish lakes. Differences with the earlier study (Rask 1993) may have been accounted for by the provision of 50 meter protective buffer zones around the lakes, mitigating the earlier observed effects. Scully et al. (2000) found relatively constant concentrations of pigments from cryptophytes, chlorophytes, and cyanobacteria in a sediment core from a Michigan lake, suggesting that epilimnetic phytoplankton were generally unaffected despite over a century long record of harvest and fire disturbance.

Anecdotal observations of increased growth of periphytic diatoms on fishing gear in the Finnish lakes subject to catchment forestry support the view that in lakes diatoms become more abundant after catchment forestry (Rask et al. 1998). Considering only disturbed lakes, Planas et al. (2000) found that algal biomass was proportional to the fraction of the catchment area disturbed divided by the surface area of lakes in the catchment.

Planas et al. (2000) examined both phytoplankton and benthic algal chlorophyll *a* and biomass in Quebec lakes in reference and harvested watersheds. Pelagic chlorophyll *a* and biomass concentrations showed significant increases between lakes (burned and harvested) with greater than 10 percent of the catchment disturbed. Although harvesting minimally changed the phytoplankton community composition, the abundance of some taxa such as Chrysophytes, Cryptophytes, and Dinoflagellates increased. More pronounced changes occurred in lakes with watershed fire one year after disturbance, as diatoms became the dominant taxa and cryptophytes increased in abundance. Concentrations of chlorophyll *a* in three lakes with watershed fire were three times the concentration in reference lakes and two times that of lakes with harvested watersheds. Biomass decreased in harvested lakes and increased in burned lakes two years after disturbance. Planas et al. (2000) hypothesized that because nitrogen export decreases with time and phosphorus continues to increase, favourable conditions may develop for blooms of potentially toxic cyanobacteria (Paerl 1988; Paerl 1996; Hyenstrand et al. 1998).

Deep chlorophyll maxima (DCM) are sensitive to minor changes in nutrient status or water clarity and can be used as a bioindicator of changes in lake water quality (Battoe 1985;

Kettle et al. 1987; Christenses et al. 1995; Knapp et al. 2003). Reduced dissolved organic matter (DOM) concentrations are known to strongly stimulate deepwater blooms in Michigan lakes (Leavitt et al. 1989, 1993; Hurley and Watras 1991 all reviewed in Scully 2000). In a study of deep chlorophyll maxima in four lakes Ontario Canadian Shield lakes subject to different levels of catchment disturbance, no dramatic changes in DCM were observed throughout the four-year study period (Knapp et al. 2003). This corresponds with Steedman's (2000) work which found only small changes in major nutrients resulting from the catchment disturbance although, DCM moved upward in the water column erratically, corresponding to reduced water clarity associated with increased DOC concentrations. Scully et al. (2000), through paleoinvestigation of Long Lake in Michigan, hypothesized that increased mixing of the lake following clear-cut harvesting eliminated obligate anaerobic photosynthetic bacteria.

While large increases in water temperature may be a major stressor on the aquatic environment, these increases, may increase primary productivity of the system (Nip 1991). However one may hypothesize that increased temperature and decreased wind protection through loss of shoreline trees may decrease habitat for cold-water dependent macroinvertebrates and salmonid fish.

2.4.3 Effects on zooplankton

Patoine et al. (2002) found zooplankton in burned lakes with watershed fire in the eastern boreal forest of Quebec shifted toward larger organisms. They hypothesised that this was related to a smaller population of young yellow perch. Furthermore, increases in DOC can create a refuge for larger crustaceans against vertebrate predators. Rask et al. (1998) observed that crustacean density was unaffected when less than 35 percent of the catchment surface area had been clear-cut in Finland. Pinel-Alloul et al. (1998) noted that zooplankton biomass and zooplankton density were, on average, significantly higher in Quebec lakes impacted by forest fire than reference or lakes with watershed harvest. While forest-harvesting increases nutrient concentrations, there is an indication that increased DOC concentrations limit light levels in these lakes and therefore primary production. On the other hand, Pinel-Alloul et al. (2002) noted members of the zooplankton group calanoids, characteristic of clear and oligotrophic lakes, were affected negatively by logging.

Patoine et al. (2000) determined that fire and harvesting seems to have an opposite effect on zooplankton to each other in the first year following disturbance. One year following a fire, lakes with burned watersheds supported 59 percent more rotifer biomass whereas harvested systems supported 43 percent less calonoid biomass. These effects appeared to be short lived as limnoplankton size class distributions stabilized after three years such that there were no significant differences between lakes with reference, harvested and burned watersheds.

2.4.4 Effects on Macro-invertebrates

Stream sedimentation can adversely affect macro-invertebrate populations (McCart and DeGraff 1974; Rosenberg and Snow 1975; Rosenberg and Wiens 1975; Quoted in Nip 1991). These effects include reduction in light penetration, reducing photosynthetic productivity and subsequently food production, an increase in abrasion of respiratory and excretory organs, reduction of habitat, species diversity and biomass. Generally in stream systems with sedimentation, the community structure can change from being dominated by Ephemeroptera, Plecoptera and Trichoptera to one dominated by Diptera (Chironomidae) (Hynes 1970 quoted in Nip 1991). Haggerty et al. (2004) observed an increase in collecting and shredding macroinvertebrates post logging in headwater Washington streams. This was attributable to increases in detrital food supply related to increased slash in the logged streams. Kreutzeiser et al. (2005) observed that a two fold increase in fine suspended sediment resulting from selected logging in a stream buffer in a hardwood forest near Sault Ste. Marie, Ontario, significantly altered benthic habitat quality and increase the abundance of five gatherer taxa Baetis, Eurylophella, Paraleptophlebia, Dolophilodes and, Tanytarsinimainly. Though some taxa increased, these effects were not considered major alterations to the ecosystem. The effects on invertebrates and water quality in this logging study seemed to be mitigated by selective logging under best management practices. Fuchs et al. (2003) found little difference in invertebrate biomass and chlorophyll a between streams of the sub-boreal central interior region of British Columbia historically logged 20-25 years before sampling. This indicated that if changes to invertebrate and phytoplankton production occur, they are not long term. However, recently logged streams (logged to the stream bank within five years preceding the study) had approximately twice the macro invertebrate biomass of reference streams and higher chlorophyll *a*. This indicated a possible immediate term increase in stream productivity resulting from the logging.

Concerning forest fire, Minshall (2003) reviewed the responses of stream benthic macro-invertebrates to fire. Minshall (2003) found that, in most cases, recovery from forest fire in streams affected by riparian fire was rapid (within 5-10 years) and changes were associated only with intense crown fires burning the majority of a catchment. Short-term effects may include temperature rise due to fire and inputs of ash and charcoal suppressing the availability of the food supply (e.g. growth of attached diatoms). Concerning trophic effects on the feeding guild composition, scrapers are expected to increase in abundance over shredders reflecting increased growth of periphyton associated with nutrient release and increased light from the opening of the forest canopy (Minshall 2003).

Salvage logging in burned watersheds can potentially lead to cumulative effects of erosion and removal of woody debris negatively effecting stream macroinvertebrates. Minshall (2003) suggests salvage logging be restricted to removal of 25 percent of the merchantable timber and ground disturbance should be avoided. Inputs of large woody debris are important in habitat creation, soil stabilization, and prevention of runoff during recovery of stream ecosystems from fire disturbance (Minshall et al., 1989; Lawrence and Minshall, 1994). Thus riparian vegetation should be maintained.

It is unclear what effect forest harvesting has on macro-invertebrates in lakes affected by catchment disturbance. It can be expected that given smaller interface between land and water in lake ecosystems compared with streams that effects would be weaker in magnitude than those observed in stream ecosystems. It is likely that effects would be indirect, for example increased lake primary productivity due to nutrient enrichment leading to increased macro-invertebrate biomass.

2.4.5 Effects on fish

The production of fish populations is principally tied to water quality and, in turn, healthy fish communities have significant economic, recreational and intrinsic value in Shield lakes. Increased transportation of particulate material can smother the eggs of spawning fish and other biota. In addition, suspended sediments fine enough to be transported around the lake may be deposited in spawning areas; however, a suitable stream buffer is believed to prevent major alterations to spawning habitat.

Temperature increases are a direct threat to cold water fish populations such as salmonids. Logged catchments supported lower densities of brook trout in Quebec (Berube and Levesque 1998). In Alberta, warmer stream temperatures correlated highly with shorter time periods in reaching peak spawning, hatching and emergence (Nip 1991). However in northern Ontario, Gunn and Sein (2000) found forest harvesting had no observable effect on lake trout (*Salvelinus namaycush).* The fact that lake trout rarely spawn in stream systems, which are most sensitive to disturbance, likely accounted for this. Spencer et al. (2003) observed fish kills in streams immediately after passage of a fire storm in Montana. This was likely due to direct temperature effects although there were probably cumulative effects smoke gasses diffusing into the stream and high ammonia concentrations resulting from the fire.

Hypolimnetic oxygen depletion and fish kills have been observed following clear cutting and mechanical site preparation in Finland (Turkia et al. 1998). In contrast, Scully et al. (2000) hypothesised that improved mixing subsequent to forest removal will improve deep-water oxygen concentrations thereby reducing winterkill in Long Lake, Michigan. In general, dramatic changes in fish populations do not seem to be a common occurrence immediately after watershed disturbance in lakes (Rask et al. 1998, Steedman, and Kushneriuk, 2000). However, this may not always be true. The proportion of small yellow perch (P*erca flavescens*) and white sucker (*Catastomus commersoni*) have been found to be significantly lower in Quebec lakes with watershed harvesting (St-Onge and Magnan 2000; Pinel-Alloul et al. 2002). This indicates a possible effect on recruitment or survival of young fish. Tonn et al. (2003) found the predominant factor influencing fish species assemblage was catchment slope and maximum depth in the Boreal Plain of Alberta. Lakes with low slope catchments were predominantly shallow in depth and had small-bodied fish assemblages. Catchment disturbance did not explain differences in the fish assemblages although the limited (two-year) study period could be a factor in this. Landscape disturbance may have the potential effect to deplete winter oxygen concentrations, translating into increased severity and frequency of winterkill (Tonn et al. 2003, Prepas et al. 2001). If nutrient enrichment occurs and is followed by increased algal biomass the potential exists for increased winter oxygen depletion. Shallow, poorly stratified lakes would be most sensitive (Tonn and Magnuson 1982).

Gunn and Sein (2000), in an innovative nine year study, artificially removed spawning habitat of lake trout (*Salvelinus namaycush)* in a northern Ontario lake, and found that while the fish were able to tolerate substantial losses in spawning habitat, increased fishing pressure because of access through forestry roads was the biggest threat to the species. Only five months after fishing began, the population was reduced by approximately 72 percent. It appeared that access and the consequent increases in angling pressure that the road created had a far greater impact on the lake trout populations than any spawning habitat loss due to sedimentation (Gunn and Sein 2000).

2.5 Longevity of impacts

The extent and duration of the effects of logging and fire on aquatic ecosystems are largely unknown (Tonn et al. 2003). Johnson and Jones (2000) found that stream temperatures in an Oregon clear-cut catchment returned to preharvest concentrations after 15 years. Martin et al. (2000) found that following harvesting experiments at Hubbard Brook Experimental Forest in central New Hampshire, water yield and peak flow increases disappeared within four to six years due to rapidly re-growing vegetation. Research by Swank et al. (2001) in the southern

Appalachian Mountains also supported this. In this study stream flow returned to normal concentrations five years after disturbance. Stream chemistry changes of increased calcium, potassium, nitrate, and hydrogen ion concentrations returned to nearly pre-harvest concentrations within three to five years.

Nicolson (1975) concludes that commercial clear cutting in the boreal forest of Ontario did not appear to have a large effect on water quality and the observed effect of increased temperature and decreased pH was short-lived. Paterson et al. (2000), using a paleolimnological approach, found minimal historical changes in the diatom species assemblage in a Northwestern Ontario lake. The small drainage ratio (1.6) and a limited fire reoccurrence (1 or 2 in last 160 years) may have been a factor in these findings; however, beginning in the early 1980s, distinct changes were noted in the species assemblage and in diatom-inferred total phosphorus, indicating possible precipitation inputs of nutrients (Paterson et al. 2000).

Multi-year studies suffer from confounding interannual precipitation patterns (Carignan et al. 2000; Prepas et al. 2003). There is a need for long term monitoring. Many studies cite a return to normal conditions shortly after disturbance whereas others conclude the impacts of forest management on lakes appear to be long lasting (Ahtiainen 1993, Turkia et al. 1998). Pinel-Alloul et al. (2002) noted ionic composition returned to normal concentrations within three years after forest fire and forest harvesting in Quebec; however, increases in phosphorus, nitrogen and DOC concentrations seemed to occur for a longer period. Martin et al. (2000) found significant alterations in calcium, potassium, and nitrate export from pre-disturbance concentrations existing 27 years after forest harvesting in a northern hardwood forest. In conifer forests of the Boreal Shield of northern Ontario, losses of base cations (potassium, calcium' magnesium) nitrate and total P (TP) above background rates may last for five to nine years following wildfires (Wright

1976; Bayley and Schindler 1991).

Carignan et al. (2000) found in Quebec that while DOC concentrations were still increasing two years after fire disturbance, a significant decreasing trend was observed in five lakes with watershed harvested. It is interesting to note this was not accompanied by parallel trends in decreases of light extinction. That is, the lake remained "clouded" despite reductions in DOC. Total phosphorus showed a similar increasing trend as DOC in the lakes with watershed harvest. Carignan et al. (2000) also found effects such as increases in potassium, chloride, nitrate and sulphate concentrations to last only one to two years. Changes in DOC, light extinction and total phosphorus seem to take longer. Increased DOC can reduce the mixing depth and depth of the euphotic zone, possibly hampering primary production. Following harvesting and burning of logging waste in the watershed of a Finnish lake, Rask (1993), observed that while mean total concentrations of phosphorus started to decrease following the treatments, total nitrogen increased to its highest concentration at the end of the five year study period. The increased availability of nitrate was likely related to an increased mixing of the water column, re-suspending nutrients from the hypolimnion. Indeed, the effects of clear-cut on mixing regimes in lakes may be more long-lived (up to 100 years; France 1997, Scully et al. 2000). Forest harvest reduced deepwater chrysophyte abundance in Long Lake in Michigan during much of the twentieth century, although partial lake recovery of the phytoplankton community has taken over 75 years (Scully et al. 2000). Citing a return of memetalimnetic blooms of chrysophytes and other once common taxa, Scully et al. (2000) conclude that complete recovery from clear cutting though slow is imminent.

2.6 Effects of repeated disturbance on water quality

Turkia et al. (1998) examined palaeolimnological records of small lakes subject to catchment forestry in Finland. Sedimentary records of some of the lakes indicated a shift in trophic status from oligotrophic to eutrophic most likely a result of repeated forest harvesting and drainage. In other lakes, the changes were less pronounced. Diatom assemblages indicated an increase in humic matter in the lakes and records indicate periodic blooms of cyanobacteria reflecting high nutrient concentrations. The nutrient load in some lakes was likely highly influenced by draining the nearby peat land and adding fertilizer to enhance forest productivity.

2.7 Best management practices

Best management practices concerning forestry operations have been reviewed in detail elsewhere (e.g. Jewett 1996; Flynn 1997; Peacock 1999). Best management practices include pre-harvest planning to avoid sensitive areas, avoiding erosion prone areas, streamside management zones (buffer strips of un-harvested vegetation), broad-based dips, water bars, and post-harvest seeding. Broad based dips are gentle waves on forestry roads to direct water off the road preventing erosion. The goal of post harvest seeding is to stabilize exposed soil. A water bar is a shallow trench and a mound which intercepts runoff from inactive roads and trails. Additionally reducing stream crossings, limiting road access, mulching disturbed areas to stabilize exposed soils, avoiding harvesting near wetlands, avoiding operations on saturated soils, locating refuelling and lubricating in a designated site may be affective management practices. In order to be effective, best management practices need to be economically viable and practical.

Lakes with a drainage ratio greater than 4 and with more than 30 percent of their watershed perturbed are the most sensitive to fire and logging (Pinel-Alloul et al. 2002). However, in the nutrient rich Boreal Plain of Alberta, Prepas et al. (2001) found harvesting an average of, as little of 15 percent of the watershed (range 3–35 percent) was associated with elevated P concentrations, cyanobacterial abundance, and cyanotoxin production in lakes. Soil conditions appear to be an important factor in assessing watershed harvesting impacts. Enach and Prairie (2000) demonstrated that fires can double the phosphorus concentration in Lac Francis Quebec. If this holds true for other areas, this provides a management rule such that logging be permitted to the extent that alterations to water quality are not larger than those of natural perturbations.

It is believed many of the effects of forestry operations can be mitigated with buffer strips. Buffer strips are believed to act as physical filters that remove sediment from transporting water (France et al. 1998). Riparian buffers may be important in controlling stream temperature and may limit algal productivity through shading (Boothroyd et al. 2004). However, the use and size of buffer strips needs careful consideration as avoiding riparian vegetation may increase the overall road length required to harvest an area; increasing the risk of sediment runoff (Quinn et al. 2004).

In an examination of the effectiveness of buffer strips in New Zealand, Quinn et al. (2004) compared the physical and chemical characteristics of streams with buffered and un-buffered shores. Streams with buffers averaging 18 meters showed only minor differences in light levels, suspended organic matter, periphyton biomass, suspended sediment, channel stability, streambank erosion, and temperatures from reference sites. However, in clear cut reaches with either patch buffers or without buffer strips, richness, relative abundance and numbers of the common taxa mayfly, stonefly and caddisfly declined significantly with clear cut logging ranging from 25-100 percent of the catchment.

Though Martin et al. (2000) found sediment yields increased during and after harvesting, these were contained by careful use of best management practices legislated by the state of New Hamshire. Nisbet et al. (2002) found the United Kingdom's Forestry Commission's Forest and Water Guidelines (Forestry Commission 1993) Guidelines were effective at mitigating any noticeable harvesting impacts on water quality in two Scottish catchments.

Plamondon et al. (1976) found that while concentrations of suspended sediment approached 100 mg/L in an unprotected Quebec stream following crossings by logging equipment, with provision of a 6 to 13 meter wide buffer strip, concentrations remained below 2 mg/l for the majority of the time. Johnson and Brondson (1995), (quoted in Nisbet 2001) demonstrated that logging truck traffic was responsible for 2- to 10-fold increases in sediment yield from road surfaces in Scotland. A drainage system consisting of vegetated buffer strip prevented the bulk of the sediment from entering water bodies. However, Prepas et al. (2001) found no evidence that buffer strip width influenced lake response after watershed harvesting in Alberta suggesting that activities within the entire watershed should be the focus when evaluating catchment–lake interactions. Steedman (2000) hypothesized that shoreline buffer strips around boreal forest lakes may be more important for preservation of aesthetic values and terrestrial habitat than for protection of water quality and fish habitat during forestry operations.

Shoreline vegetation has lower tree density and smaller tree size than upland areas, and may be less able to filter sediment from watershed clear cutting than was once believed (France et al. 1998). This is an important consideration when deciding the minimum size of buffer strips. It is interesting to note that in Ontario there has been a decrease in the recommended width of buffer strips from 120-180 meters to 30-90 meters (see France et al. 1998). The rationale for these changes was not clear.

Steedman and Kushneriuk (2000) describe how a forested shoreline buffer strip around one northern Ontario lake prevented increases in midlake wind speed but did not prevent declines in water clarity and thermocline depth. Nicholls et al. (2003) explained how less extensive logging of one drainage basin and the maintenance of an unlogged buffer strip along the shoreline did not prevent changes to the phytoplankton community compared with two other north western Ontario lakes with more extensive logging of their catchments. Further research is merited in this area.

2.8 Summary

Based on the literature the following general observations can be made. The extent to which forest removal affects aquatic ecosystems is variable across lakes and is correlated to the size of the disturbance relative to the watershed to lake area ratio. The watershed to lake area ratio and watershed to lake volume ratio is a measurement of the relative rate of water movement. Lakes with a high watershed to lake area or watershed to lake volume ratio are most sensitive to catchment disturbance. In harvested watersheds, road building activity and soil disturbance will cause the greatest effects on aquatic ecosystems. Forest removal will increase water yield in stream ecosystems. This in turn can influence the timing of maximum spring water levels in lakes. Decreased water holding capacity of soils from removed vegetation can decrease dry season stream flows. Water temperature can increase resulting from reduced shading following loss of riparian vegetation. Riparian harvesting and or fire can lead to increases in lake wind velocity, temperature and changes to the mixing regime.

Though the effects of forest harvesting and fire are similar they are not the same (Table 5). Phosphorus and nitrogen concentrations increase with both harvesting and fire, however nitrogen concentrations typically increase more with fire (likely due to mineralization of the litter layer) and phosphorus concentrations generally show greater increases in harvested systems relative to burned systems. Dissolved organic carbon increases are higher in harvested systems. Increases in turbidity from suspended sediment may affect littoral and emergent vegetation particularly near the photic depth (the depth where available light for photosynthesis becomes limiting). Cations and anions (e.g. potassium and chloride, calcium and magnesium) transportation into lakes may increase following both types of disturbance.

DOC or sediment increases may result in loss of oxygen from the hypolimnion due to the decomposition of organic material. DOC concentration is related to mercury methlylation in aquatic ecosystems. The link between elevated DOC increases and high mercury concentrations in fish and other biota warrants further study. Changes in algal productivity and species composition may result following watershed disturbance. This is primarly related to increases in nutrient availability. Observed changes in species composition from chlorophyceans and chrysophyceans to diatoms and blue-green algae have been noted. Effects on fish and other biota seem inconclusive; however, there is evidence that recruitment or survival of younger age classes of fish may be affected by watershed disturbance.

The longevity of the impacts of forest disturbance on water quality is highly variable. A few studies cite returns to pre disturbance conditions two to five years following fire or harvesting, others suggested that recovery may take up to 75 years. Repeated watershed disturbance is likely to lead to an increase in overall productivity. Normally succession of lakes is a slow process. The extent to which long term forestry activities can accelerate this process is not known. The longevity of impacts and the effects of repeated disturbance on water quality warrant further attention. Best management practices typically attempt to minimize soil disturbance and erosion thereby protecting water quality. Buffer strips effectiveness is accredited to their role as physical filters. The extent to which buffer strips protect water quality and the minimum width of buffer strips are sources of debate. While buffers seem to be effective in some areas, they are of limited use in others.

In Canada, the geographic scope of research is limited. For example the majority of studies have focused on lakes in Alberta, Ontario, or Quebec. The diversity of results observed and the vast nature of the country necessitates further research into the effects of watershed disturbance on lake water quality.

Table 5: Summary of the expected effects of forest management on various chemical and physical water quality parameters Note: Key limnological characteristics are likely influenced by catchment and morphometric properties such as the drainage ratio (DR), mean residence time, and watershed slope (Carignan et al. 2000; Schindler 1971; Engstrom 1987; Rasmussen et al. 1989).

	Forest Harvesting		**Wildfire**	
Parameter	**Effect**	**Source(s)**	**Effect**	**Source(s)**
Secchi Depth	**Decrease**	Beaty 1994	**Decrease (?)**	
Photic Depth	**Decrease;** attributable to increased DOC	Beaty 1994, Kushneriuk 2000	**Decrease**; less than harvesting, incident light levels will **increase**	
Turbidity	**Increase**	Beaty 1994, Nisbet 2001	**Unknown**	
Sedimentation	**Increase**	Steedman and France (2000)	May **increase** depending on intensity of fire	
Temperature	**Increases** (particularly in stream systems) depending on buffer size	Nicolson 1975, Johnson and Jones 2000, Steedman et al. 2001	**Increase (?)**	
Hypolimnetic oxygen	**Decreased** due to increased nutrient supply, sediment load and DOC	McNamee et al. 1987	Possible **decrease** due to increased nutrient levels, algae production and decomposition	
Epilimnion Depth	**Reduced** (attributed to decreased wind protection)	Rask et al. 1998, Steedman 2000	Likely **reduced** due to decreased wind protection depending on severity of fire	
pH	**Reduced** due to increases in sulphate export and organic acids	Nicolson 1975, Krause (1982)	**May increase or decrease**	Rhodes and Davis (1995) and Korhola et al. (1996); Enach and Prairie (2000)
Phosphorus	**Increased** (mostly in organic forms)	Likens et al. 1970, Rask et al. 1993	**Increased;** increased over harvesting, increased significantly over reference	Schindler et al. (1980); Tonn et al. (2003); Prepas et al. (2002); McEachern et al. (2002)

Nitrogen	**Increased** (mostly in organic forms)	Likens et al. 1970, Rask et al. 1993	**Similar to forest harvesting;** greater than harvesting; Increased over reference	Lamontagne et al. (2000); Tonn et al. (2003); Prepas et al. (2002); McEachern et al. (2002)
Nitrate	**Increase;** due to binding and export with base cations	Likens et al. 1970; Dahlgren and Driscoll 1994	**Increased,** nitrate released by fire generally in inorganic forms and organic forms by forest harvesting	Carignan and Steedman 2000; Lamontagne et al. 2000
Dissolved Organic Carbon (DOC)	**Increased** from watershed export	Beaty 1994	**Increased;** difference not significant from harvested	Carignan and Steedman (2000), Carignan et al. (2000)
Calcium	**Increased**	Likens et al. 1970, Bormann and Likens 1979; Hornbeck et al. 1986; Johnson 1995; Martin et al. 2000	**Similar to forest harvesting** although in inorganic forms; 2-4x higher than forest harvesting	Lamontagne et al. (2000); Carignan et al. (2000)
Magnesium	**Increased**	Likens et al. (1970), Bormann and Likens (1979); Hornbeck et al. (1986); Johnson (1995); Martin et al. (2000)	**Similar** to forest harvesting although in inorganic forms; 2-4x higher than forest harvesting	Lamontagne et al. (2000); Carignan et al. (2000)
Sodium	**Increased**	Likens et al. 1970, Bormann and Likens 1979; Hornbeck et al. 1986; Johnson 1995; Martin et al. 2000	**Similar** to forest harvesting	Lamontagne et al. (2000)
Potassium	**Increased** more than fire	Carignan et al. (2000)	**Increased** although not as much as harvesting	Carignan et al. (2000)
Chloride	**Increased** more than fire	Carignan et al. (2000)	**Increased** although not as much as harvesting	Carignan et al. (2000)
Mercury	**Possibly increased;** due to association with DOC; high DOC loads associated with high concentrations in Zooplankton and Fish	Rask et al. (1998), Garcia and Carignan (1999), Carigan et al. (2000), Porvari et al. (2003)	**Not significantly different from harvested or reference**	Garcia and Carignan (2000)

3.0 Methods:

3.1 Study area

The water of 99 lakes was sampled once by means of a floatplane in a geographic area along the east side of Lake Winnipeg from the southern border of Nopiming Provincial Park to, and including, Atikaki Wilderness Park (Figure 4) in the summer of 2004. In 2005, 21 of these lakes were sampled in May, August and September (refer to section 3.2.2). For many of the lakes in the survey, this was the first time that water quality data has ever been collected, thus providing important baseline information.

Lakes were selected by means of a flight over the area, an examination of GIS layers of disturbance history and an evaluation of existing water quality data. An aerial reconnaissance flight took place on July 8, 2004. Lakes were selected to represent a broad range of watershed characteristics, lake sizes (small lakes versus the largest lakes of the region) and watershed disturbance (forestry and forest fire). Of these lakes, 12 had harvested watersheds as evidenced by aerial observations. Including these, 22 lakes had harvesting in their catchments as indicated by GIS data from 1983-2003. Twenty lakes had watersheds burned by forest fire with several recent burns (since 2003) in the northern portion of the study area in the proximity of Dogskin Lake and Sasaginnigak Lake. Two lakes (Rice Lake near Bissett and Bernic Lake) have mining operations located on their shores. Approximately five of the lakes sampled had extensive cottage developments. There were fishing lodges and outposts on many of the northern lakes.

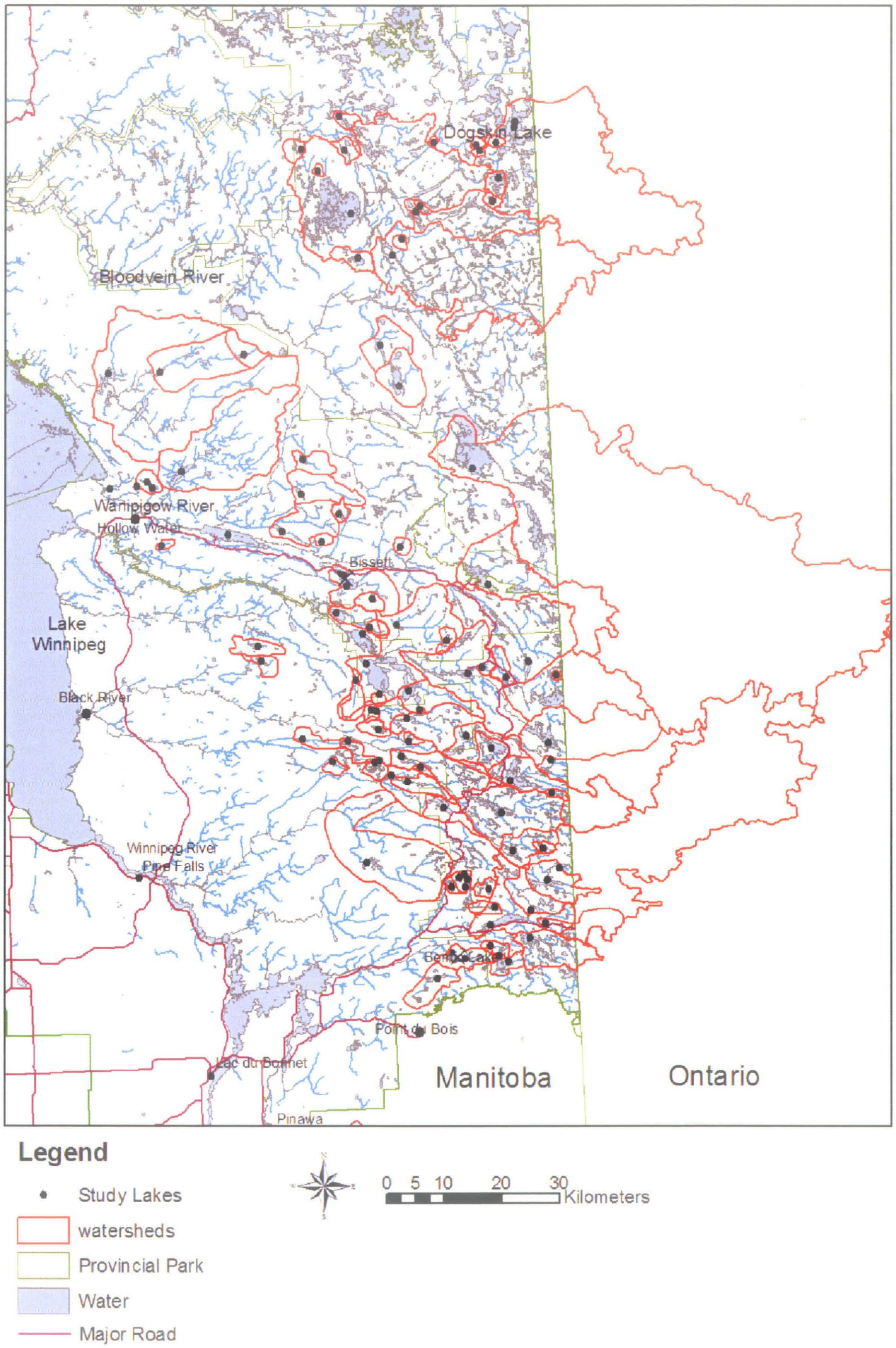

Figure 4: Map of the study lakes and their associated watersheds

Black dots represent sampling locations in 2004. Note: 25 of the 99 lakes sampled in 2004 had a portion of their watersheds originating in north western Ontario, GIS data excluding watersheds courtesy Tembec Industries Inc. Pine Falls Operations.

3.2 Water sampling

3.2.1 Year 1: Summer 2004

Each lake was sampled once in 2004. Sampling occurred in 99 lakes between July 26th and August 11th 2004 (Figure 4, Table 6). Sampling occurred from the pontoon of a float equipped Piper Super Cub aircraft. Sampling was generally conducted at the deepest location or centre of each lake unless weather conditions and/or safety necessitated anchoring at a wind-protected location. The anchor was lowered gently taking care not to disturb the sediment. Epilimnion water samples were collected using a sampler consisting of a flexible two metre (~3.5 cm diameter) clear PVC tube with a weighted one-way check valve to a standard depth of 2 metres (this was reduced where warranted by shallow conditions of the lake). Both the sampler and sample bottles were triple rinsed in lake water before sampling each lake. One sample was collected at each site with triplicate samples from the same site at approximately every 15 lakes for quality assurance. Water samples were collected in 500 ml Nalgene bottles and were kept on ice in the dark and transported to the laboratory within 48 hours for analysis.

Hypolimnion samples were obtained from 8 lakes (Table 6). Deep-water samples were obtained from two meters above the sediment as indicated by Sonar. Samples were collected using a weighted Van-Dorn sampler lowered on a graded rope.

Additional surface water samples were collected in 100 ml containers pre-acidified with nitric acid for trace metal analysis of lake water. For quality assurance triplicate samples were collected at approximately every 10 lakes. These samples were sent to the Ultra Clean Trace Elements Laboratory at the University of Manitoba and are pending analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Anticipated analysis include concentrations of Ag, Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cs, Cu, Fe, Ga, In, K, Li, Mg, Mn, Na, Ni, Pb, Rb, Se, Sr, Tl, U, V, Zn.

One phytoplankton sample from each lake was collected for species identification using several vertical hauls from one metre above the sediment to the surface with a phytoplankton tow net (20 µm pore size). The net was rinsed twice before sampling each lake to prevent cross-lake contamination of samples. Phytoplankton samples were preserved to a final concentration of 2-4 percent formalin and were sent to Dr. Gordon Robinson at the University of Manitoba for algal species identification. These data are forth coming.

Secchi disk depths were collected for each lake using a 20 cm diameter Secchi disk lowered on a nylon rope. Readings were taken from the pontoons of the aircraft in the shade. Vertical extinction of photosynthetically available radiation (έPAR; 400-700 nm) was measured using a Licor LI-193 spherical underwater sensor connected to a LI-1000 data logger (Licor Biosciences, Lincoln, Nebraska U.S.A) attached to a frame that was lowered at metre intervals. Measurements were taken on the sunny side of the aircraft. Simultaneous readings were recorded from a terrestrial sensor were used to correct for any change to the underwater light readings by changes in cloud cover. The photic depth (where light reaches one percent of incidence levels) for each lake was calculated by linear regression of light extinction data.

Dissolved oxygen, conductivity, and water temperature measurements were collected at 1 metre depth intervals using YSI Model 85 probe with a 15 metre cable (YSI Incorporated, Yellow Springs, Ohio). pH was measured in the field using a Fisher Accumet AP61 portable meter.

The location and depth of each site was recorded using a Garmin GPS Map 168 sounding receiver. Basic bathymetric data were collected for each lake by transecting along one axis of each lake and marking depths at approximately 100-metre intervals. Shoreline and observations of watershed fire and forestry were made for each lake when circling from the air. Digital photographs of all lakes were collected from the air.

Water samples were analysed in Winnipeg at the Freshwater Institute (Fisheries and Oceans Canada) according to standard methods (Stainton et al. 1977; Table 7). Analysis included: dissolved nitrate/ nitrite (μg/L), suspended nitrogen (μg/L), total dissolved nitrogen (μg/L), suspended phosphorus (μg/L), total dissolved phosphorus (μg/L), dissolved inorganic carbon (μg/L), suspended carbon (μg/L), dissolved organic carbon (μg/L), chlorophyll *a* (μg/L), chloride (mg/L), sulphate (mg/L), sodium (mg/L), potassium (mg/l), calcium (mg/L), magnesium (mg/L), soluble reactive silica (mg/L), pH, conductivity (μS/cm), and alkalinity (μeq $CaCO_3$/L).

Table 6: Locations of 99 boreal lakes sampled for water quality during 2004 and 2005
Note: Latitude and Longitude in decimal degrees. **H** = hypolimnion sample collected in 2004, * = Sampled in both years, **X** = Lake removed during 2005 sampling program because it was too small for the aircraft to land safely. Note: Lake 17 omitted from the list as it was the same lake as Lake 7.

LAKE ID	LAKE NAME	Latitude	Longitude	Notes	LAKE ID	LAKE NAME	Latitude	Longitude	Notes
1	Elbow lake	50.53527	95.21563		48	Atiko	51.37547	95.90924	H
2	MacGregor	50.55295	95.18560		51	English	51.19778	96.07590	
3	Lincoln	50.58590	95.22282		52	Dawson	51.17272	96.14991	
4	Cole	50.58407	95.29612		53	Boulette	51.18359	96.16218	*
5	Lapin	50.52694	95.36145		58	Farrington	50.89637	95.89633	*
6	unnamed	50.53129	95.41830		56	unnamed	51.08286	96.13107	
7	Metcalf	50.54230	95.41014	*, X	57	Owl	50.92056	95.90212	*
8	Kinsley	50.54612	95.43195	*	59	unnamed	51.59674	95.26730	*
9	Springer	50.53235	95.45170	*	60	unnamed	51.63333	95.24990	*
10	Bird	50.46992	95.36133		61	Dogskin	51.70910	95.20342	
11	Tulibi	50.48941	95.25891		62	unnamed	51.68739	95.25027	
12	Starr	50.46820	95.22513		63	unnamed	51.68470	95.30063	*, X
13	Booster	50.44631	95.26499		64	unnamed	51.67537	95.29350	*
14	Blue	50.42101	95.34245		65	Manning	51.69184	95.40797	*, X
15	Birse	50.41132	95.32171		66	unnamed	51.58539	95.46112	
16	Eastland	50.49723	95.34896	*	67	unnamed	51.59464	95.44853	*
18	Glen lake	50.72112	95.51319	*	68	unnamed	51.54469	95.49938	*, X
19	Terminal	50.69901	95.54714	*	69	Gordon	50.73109	95.62586	H
20	Maskwa	50.57623	95.65609		73	Gold	50.98596	95.61340	
21	Bernic	50.41838	95.42515		74	Rainy	50.94363	95.55788	*, X
22	Shatford	50.39052	95.49545		70	Gilmour	50.77237	95.80257	
23	Rush	50.43685	95.36241		71	Little Beaver	51.07919	95.73371	
24	unnamed	50.55057	95.41849		72	Rice	51.00868	95.67645	
25	Lost Claim	50.67021	95.19368		75	Kawaseecheewonk	51.51934	95.52452	H
26	Black	50.64437	95.31957		76	Round	51.51754	95.61108	*
27	Shoe	50.65633	95.46208		77	Sasaginnigak	51.58721	95.62344	H
29	Slate	50.72172	95.19267		78	unnamed	51.68653	95.63327	
30	Gem	50.74866	95.19569		79	unnamed	51.73950	95.64299	

31	Tooth	50.74562	95.33813	
28	Flintstone	50.69356	95.29442	
32	Moose	50.76582	95.39788	
33	unnamed	50.85302	95.16803	
34	Beresford	50.87786	95.23613	
35	Stormy	50.85479	95.29274	
36	Badou	50.87187	95.35111	
37	Long	50.8627	95.38498	
38	unnamed	50.81026	95.50872	
39	Big Clear Water	50.96716	95.70489	
40	Quesnel	50.93277	95.64113	
41	Manigotogan	50.88554	95.63634	
42	unnamed	50.86128	95.66337	
43	unnamed	50.83693	95.60715	*
44	Happy	50.8411	95.53360	*
45	Spence	50.94183	95.62327	*
46	Frenchman	50.7981	95.54214	
54	unnamed	51.17648	96.18718	
50	Shallow	51.35332	96.24842	
55	Clangula	51.174	96.25488	
47	Wanipigow	51.0957	95.96574	
49	unnamed	51.35314	96.11994	
80	unnamed	51.69071	95.74086	*
81	unnamed	51.65637	95.70248	H
82	North Eagle	51.38082	95.56586	
83	South Eagle	51.31542	95.52303	
84	Aikins	51.18274	95.34962	H
85	Hutt	50.70991	95.58702	
86	Black River Lake	50.73890	95.55835	
87	Brooks	50.76166	95.54136	H * x
88	Field	50.78191	95.61308	
89	unnamed	50.81034	95.61601	
90	unnamed	50.81369	95.62776	
91	McRorie	50.76711	95.68999	
92	West Rat	50.73511	95.73052	*, X
93	Peacock	50.73334	95.61430	
94	Faraway	50.91566	95.43532	
95	Wallace	50.99995	95.32492	
96	unnamed	51.05589	95.52591	
97	unnamed	51.12016	95.68789	*
98	Kakaki	51.20843	95.77173	*
99	Okimaw	51.15489	95.78005	*
100	Saxton	51.09742	95.83136	*

3.2.2 Year 2: May-September 2005:

Of the 99 lakes sampled in 2004, 28 of them were selected for study in 2005. Headwater lakes were selected to reduce possible upstream influences (Figure 5). Due to the fact that Piper Super Cub used in 2004 was destroyed in a crash a Cessna 172 was used in 2005. This Cessna 172 required increased takeoff and landing distance and some of the smallest lakes had to be excluded in 2005. In total 23 lakes were sampled in May, August and September.

Sampling took place at three sites within each lake in May (May 20 - 26), and single central locations in August (7 -13) and September (18 - 22). Sampling consisted of collection of water for chemical analysis. Vertical profiles of conductivity, temperature and oxygen, Secchi depth measurements and light extinction profiles were also collected. An equipment malfunction prevented light extinction readings in August and September. Sampling methods were as mentioned for 2004. Samples for chemical analysis were collected in four bottles, two one-litre bottles for chemical analysis and chlorophyll analysis, one 500ml bottle for nutrient analysis, one 250 ml bottle for analysis of cations. Samples for ions (calcium, potassium, magnesium, and sodium) were preserved in the field with the addition of 2.5 ml 20 percent concentrated nitric acid.

Water samples (excluding samples for chlorophyll analysis) were delivered to EnviroTest Laboratories in Winnipeg for analysis of total dissolved phosphorus (mg/L), total phosphorus (mg/L), ammonia (mg/L), dissolved organic carbon (μg/L), total Kjeldahl nitrogen (mg/L), total suspended solids (mg/L), turbidity (NTU), pH, total dissolved solids (mg/L), sulphate soluble (mg/L), nitrate + nitrite (mg/L), calcium (mg/L), potassium (mg/L), magnesium (mg/L), sodium (mg/L), hardness (as $CaCO_3$)

(mg/L), conductivity (μS/cm), chloride soluble (mg/L), and alkalinity (mg/L) according to standard methods (Table 8).

Figure 5: Map of samples sites in 2005:

Sampling took place in May, August and September. Black dots represent May sampling locations on each lake.

Plate 1: Pilot, Chad Bayes measuring light extinction in Lake 7, July 27th 2004.

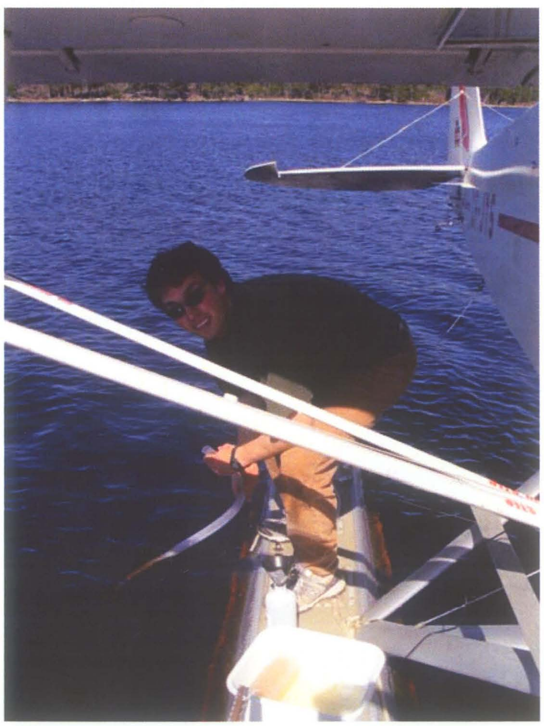

Plate 2: Kevin Jacobs sampling epilimnion of Farrington Lake

from pontoon of Piper Super Cub May 20th , 2005.

Plate 3: Forest harvesting in the vicinity of Lake 43

Plate 4: Aerial view of a shallow lake in Eastern Manitoba

Plate 5: Lake 68 with evidence of recent watershed fire

Table 7: List of analysis and methods employed in 2004
by the Fresh Water Institute for chemical analysis on raw water samples from Canadian Shield Lakes

Parameter	Detection Limit	Units	Method Employed
Nitrate Dissolved	1	µg/L	Stainton et al. (1977)
Nitrite Dissolved	1	µg/L	Stainton et al. (1977)
Suspended Nitrogen	1	µg/L	Stainton et al. (1977)
Total Dissolved Nitrogen	5	µg/L	Stainton et al. (1977)
Suspended Phosphorus	1	µg/L	Stainton et al. (1977)
Total Dissolved Phosphorus	1	µg/L	Stainton et al. (1977)
Dissolved Inorganic Carbon	60	µg/L	Infrared detection of CO_2 sparged from acidified samples
Dissolved Organic Carbon	60	µg/L	Infrared detection of CO_2 following per sulphate digestion
Suspended Carbon	10	µg/L	Stainton et al. (1977)
Chlorophyll *a*	0.01	µg/L	Gross fluorescence with 95% methanol, Stainton et al. (1977)
Soluble Reactive Silica	0.001	mg/L	Stainton et al. (1977)
Chloride	0.01	mg/L	Ion chromatography, Fee et al. (1989)
Sulphate	0.01	mg/L	Ion chromatography, Fee et al. (1989)
Conductivity	1	µS/cm	
Sodium	0.01	mg/L	Atomic Absorption
Potassium	0.01	mg/L	Atomic Absorption
Magnesium	0.01	mg/L	Atomic Absorption
Calcium	0.01	mg/L	Atomic Absorption
pH	0.01	pH units	
Alkalinity	1	µeq calcium /L	Automated titration (Titroprocessor)

Table 8: List of analysis and methods employed by EnviroTest Laboratories for chemical analysis on raw water samples in 2005.

Parameter	Detection Limit	Units	Method Employed
Total Dissolved Phosphorus	1	µg/L	APHA, 1998
Total Phosphorus	1	µg/L	APHA, 1998
Ammonia Soluble	10	µg/L	APHA 4500, 1998/ LACHAT; MAR
Dissolved Organic Carbon	100	µg/L	APHA 5310 B-Instrumental
Total Kjeldahl Nitrogen	200	µg/L	Quickchem method 10-107-06-2-E
Total Suspended Solids	5	mg/L	
Turbidity	0.05	NTU	APHA, 1998, 2130B
pH	0.01	pH units	APHA 4500B, 2510B, 2320B, 1998
Total Dissolved Solids	5	mg/L	
Sulphate Soluble	9	mg/L	APHA 4500, 1998/ LACHAT; MAR
Nitrate + Nitrite Soluble	10	µg/L	APHA 4500, 1998/ LACHAT; MAR 1997
Calcium- extractable	0.05	mg/L	EPA 200.8 Rev 5.4 May 1994
Potassium-extractable	0.05	mg/L	EPA 200.8 Rev 5.4 May 1994
Magnesium-extractable	0.01	mg/L	EPA 200.8 Rev 5.4 May 1994
Sodium-extractable	0.02	mg/L	EPA 200.8 Rev 5.4 May 1994
Hardness (as $CaCO_3$)	200	µg/L	Calculated
Conductivity	0.4	µS/cm	
Chloride Soluble	9	mg/L	APHA 4500, 1998/ LACHAT; MAR 1997
Alkalinity, Total (as $CaCO_3$)	1	mg/L	APHA 4500B, 2510B, 2320B, 1998
Bicarbonate (HCO_3)	2	mg/L	APHA 4500B, 2510B, 2320B, 1998
Carbonate (CO_3)	0.6	mg/L	APHA 4500B, 2510B, 2320B, 1998
Hydroxide (OH)	0.4	mg/L	APHA 4500B, 2510B, 2320B, 1998

Samples for chlorophyll analysis were filtered in the field (Whatman GF/C Glass microfibre). Filters were frozen for chlorophyll analysis and were analysed by methanol extraction according to the method of Marker et al. (1980). Filtrate was also analysed for dissolved organic carbon using a near ultraviolet multi-wavelength spectrophotometric scan (Badiou unpublished method). Concentrations of Chlorophyll *a* and DOC in 2005 were analyzed at the Delta Marsh Field Station (University of Manitoba).

Raw water samples were collected in 100 ml HDPE bottles for analysis of total microcystin. These were analysed by AlgalTox International (Pine Falls, MB) using protein phosphatase inhibition based on the method developed by An and Carmichael (1994) (detection limit 0.100 μg/L).

One phytoplankton sample from each lake was collected for species identification using several vertical hauls of a phytoplankton net. Phytoplankton samples were preserved by formalin injection to a final concentration of two to four percent.

3.3 Geographic Information Systems Analysis

3.3.1 Watershed Boundaries

Watershed boundaries for each lake were determined from 1:50,000 NTS maps and the Prairie Farm Rehabilitation Program's (PFRA) draft sub watershed boundaries for Manitoba. These were then digitised into a geographic information System (ArcView GIS version 3.2, ESRI 1999). Watershed areas were calculated using the X-tools extension (Oregon Department of Forestry 2003). Percent disturbance for each watershed was determined by intersecting digitized watersheds with GIS layers of disturbance history maintained by the Tembec Industries Inc., Pine Falls Operations. Hectares of recent and historical disturbance from forest fire, forest harvesting and insect and disease were determined for each watershed. The area of disturbance within each year was divided by the area of each watershed to determine the percentage of watershed disturbed in each year. The percent disturbance for each year was summed to determine the cumulative proportion of the watershed disturbed within the last 5, 15, 25, 35 and 50 years. Where watersheds originated in Ontario, this disturbance information was not available. Data analysis concerning watershed features excluded these watersheds.

3.3.2 Shoreline Development

The area and shoreline length of each study lake were obtained from the Forest Management Lease (FML) Water Database maintained by Tembec (scale 1:50,000). The Shoreline Development Index (D_L) was calculated for each lake based on the formula of Hutchinson (1957). The shoreline development measures the length of the shoreline of a lake compared to a perfectly circular shape of equal surface area, where a D_L near one represents a perfectly circular lake and a $D_L > 1$ represents a lake with more complex shoreline development. Shoreline development reflects the potential for greater development of littoral communities in proportion to the area of the lake (Wetzel 1975).

3.3.3 Forest Resource Inventory

Using the 1983 and 1997 forest resource inventories (FRI), the relationship between forest type and lake water quality in the region was examined. The most recent 1997 FRI excludes Atakaki Wilderness Park so the older 1983 forest resource inventory was used for these watersheds. The FRI category Stand Type categorises forest polygons by the dominant features of the landscape. This may be prevalent species in a stand of trees (e.g. jack pine, black spruce, balsam fir, trembling aspen) or generic landscape features such as other hardwoods, bare rock, meadow, treed muskeg, or marsh. The areas of the categories, treed muskeg, muskeg, will alder, beaver flood, and marsh were combined producing a "wetlands category" to evaluate the role that wetlands in a watershed have in influencing lake water quality. The categories trembling aspen, and all other hardwoods were merged, producing a hardwoods category. Land type and Subtype classifications were used to determine the percent of each land type, e.g. jack pine, black spruce, beaver floods, black spruce treed muskeg, bare rock and willow alder (Tembec 2002).

3.3.4 Soils

Soils data were obtained from the 1:1,000,000 Enduring Features GIS database developed by the World Wildlife Fund (1997). Soils are classified into broad categories including:

- BR/D bedrock/dark grey chernozem, BR/F- bedrock/grey brown luvisol, BR/R2-bedrock/ acidic hard rock, BR/Y23- bedrock/ organic mesisol
- DB/D deep basin/ dark grey chernozem, DB/F- deep basin/ grey brown luvisol DB/R2- deep basin bedrock/ acidic hard rock, BR/Y23- bedrock/ organic mesisol
- GD/R2 glaciofluvial deposit/ acidic hard rock
- OD/D organic deposit/ dark grey chernozem, OD/F – organic deposit/grey brown luvisol, OD/R2- organic deposit/ acidic hard rock, OD/Y23 – organic deposit/organic mesisol
- T3/R2 glacial till derived from Precambrian rock/ acidic hard rock

3.3.5 Disturbance History

Disturbance types in the boreal forest include wind, fire, insect, disease and forest harvesting. Using GIS layers of disturbance history (insect outbreaks, forest fires, forest harvesting, and mechanical soil preparation), I examined the water quality in lakes compared to their disturbance history.

3.3.6 Forest Fire

The extent of forest fire within each watershed was determined from GIS databases of recent and historical fire. Forest fire disturbance was broken into two datasets. The location of historical fires was determined from the fire history database 1881 to 1971 maintained by Tembec. This database was created from fire history maps and provides the general locations of major fire events. More recent fire distribution has been collected digitally by the Province of Manitoba since 1986. This database is updated annually and was used to determine the locations of forest fires since 1986. Since 1986 the spatial resolution of this database is much more accurate (<1 ha) as compared to earlier fire data.

3.3.7 Forest Harvesting

The extent of forest harvesting was determined from two databases. The historical harvesting GIS database was generated through old harvest history maps (1950's to 1985) and provided the approximate locations where forest harvesting took place. The historical harvesting database is maintained by Tembec. Newer harvest information like the fire history has been digitally collected by Tembec since 1986, is updated annually and is much more accurate than earlier harvest data.

3.3.8 Mechanical Site Preparation

The mechanical site preparation database has been maintained by Tembec since 1994 and was used to determine the extent and type of mechanical site preparation in each harvested watershed.

3.3.9 Insect Disturbance

The amount of insect disturbance by Forest Tent Caterpillar (*Malacosoma disstria)* and Spruce Budworm (*Choristoneura fumiferana)* were determined for each watershed using the insect disturbance database maintained by Tembec. Since 1995, information on the extent and severity of insect disturbance is collected digitally and updated annually.

3.3.10 Linear Features

Linear features can include logging roads, all season roads, trails and hydroelectric corridors. The total length of linear features within each watershed was determined from the FML Access Database and normalized against the area of each watershed. Decommissioned and reforested roads were excluded from the analysis.

3.4 Characterization of Watersheds

3.4.1 Disturbance History

Lakes were grouped based on disturbance history (in the last 50 years) into the following classes. The classes were chosen based on the minimum proportion of watershed disturbance that has been associated with changes to water quality in the literature. The proportion of disturbance was defined as amount of watershed disturbed (from the GIS database) divided by the area of the watershed.

- Reference lakes with less than 15 percent total disturbance by fire or forestry within the last 50 years (1953-2003)
- Burned watersheds with greater than 15 percent fire disturbance within the last 50 years (1953-2003)

- Harvested watersheds with greater than 15 percent harvest disturbance within the last 50 years (1953-2003)
- Watersheds with both fire and harvest disturbance totaling over 30 percent of the watershed area

3.4.2 Soil Type

Watersheds were also characterised by the proportion of each category of soil type in their watersheds from the enduring features database into the following groups. These grouping corresponded with natural groupings of the soils data.

- Catchments with greater than 50 percent deep basin and/ or organic soils,
- Catchments with approximately 20-50 percent deep basin or organic soils,
- Catchments with over 80 percent bedrock soil

3.5 Statistical Analysis:

Water quality results were compared to land use and watershed characteristics using both univariate and multivariate statistical analysis to determine the influence of land use and landscape features on the lake water quality in this region.

3.5.1 Univariate Statistical Analysis

Regression Analysis and Analysis of Variance (ANOVA) were performed using the statistical package JMPIN (ver 4.02 SAS Institute Inc.). Correlation Analysis was used to examine the relationship between water quality variables and watershed features. Analysis of Variance (ANOVA) evaluated the mean water chemistry between sampling periods, years and lakes grouped by disturbance and soil type (α =0.05).

3.5.2 Multivariate Statistical Analysis

Ordination methods reduce complex data structure, allowing comparison in a lower dimensional space. Multivariate statistical analysis used the computer program *Syntax 2000* (Department of Plant Taxonomy and Ecology L. Eotvos University, Budapest Hungary). Principle Component Analysis and Correspondence Analysis were used to analyze 2004 and 2005 data. Analysis for 2004 data included only data from watersheds originating in Manitoba.

All data except pH were standardized by log transformation using the formula log (X+1). To preserve linearity in the data, concentrations of water quality parameters with values less than two were multiplied by 1000 for Principle Component Analysis (PCA) (Macbeth 2004). Where water quality parameters were below the detectable limit of the laboratory method employed, these data were changed to zero for the statistical analysis. Water quality data contained few zeros and were analyzed using Principle Component Analysis (PCA). Correspondence Analysis (CA) standardizes data by variables and objects and is suited to linear or non-linear data. Correspondence analysis was used to compare watershed disturbance and soils data which had a large proportion of zeros. Correspondence analysis was used to compare disturbance, soils and water quality data due to its overall non-linear structure.

Chapter 4: Results

4.1 Watershed Features

4.1.1 Fire

Within the period 1998-2003 one watershed was completely burned while another watershed had 84 percent of its area burned. In the last 35 years, eleven watersheds have been completely burned by forest fire. Of these, it appears seven have been affected by more than one fire (for example, 100 percent of watershed 54 was burned by fire in 1989 and 40 percent of the area was re-burned in 1999). Fire is a significant natural ecological process in this region. Historical fire data indicates only 11 out of 99 watersheds have had less than five percent of their area burned since records began in 1885. As of 2005, recent fires taking place since 2000 were restricted to the northern section of the study area (Figure 6).

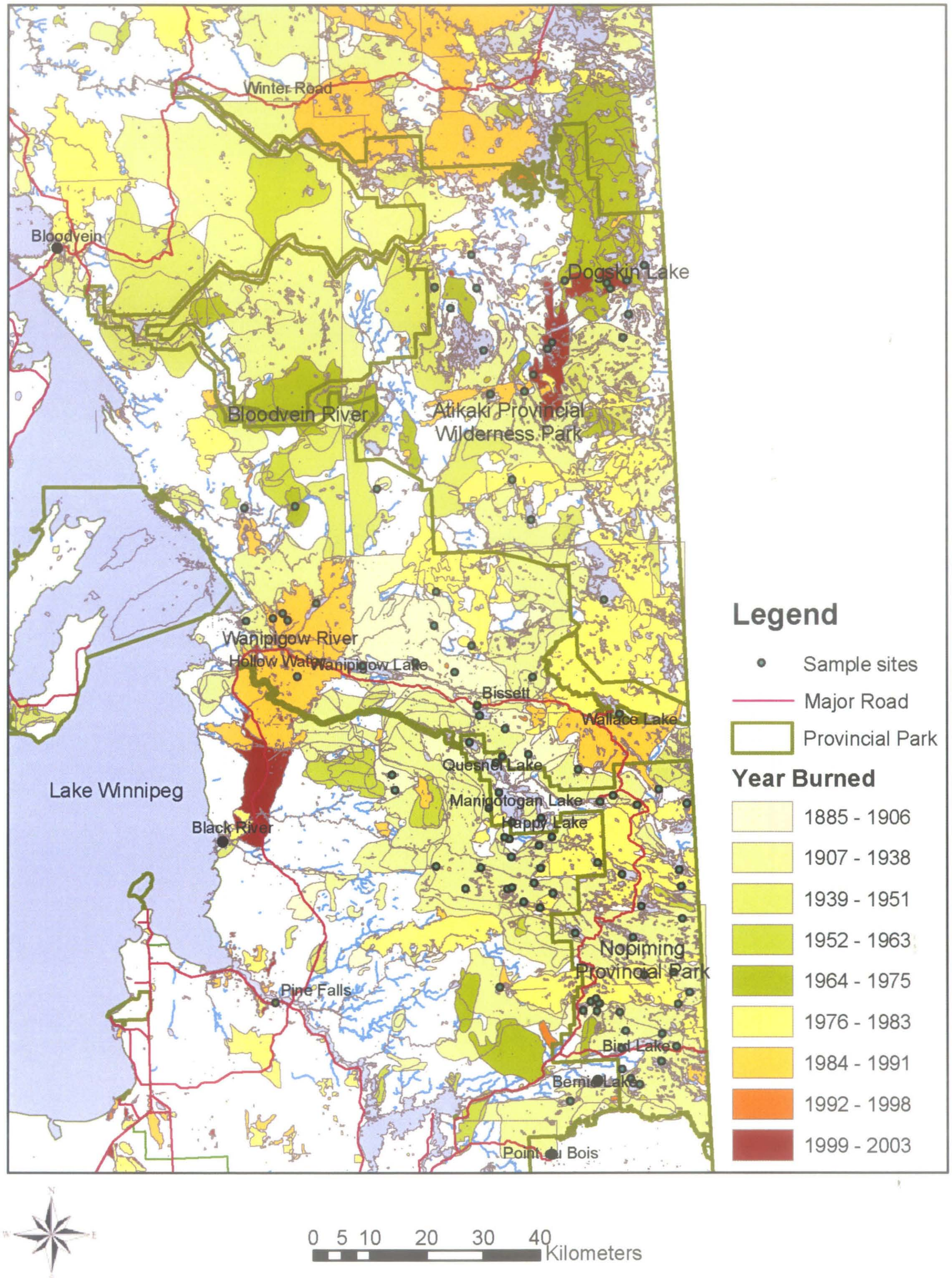

Figure 6: History of forest fire in the study area

From 1876 to 2003 84 percent of the study watersheds have been burned by forest fire. Recent forest fire is restricted to the north or extreme western portions of the study area. Data courtesy Tembec- Pine Falls Operations.

4.1.2 Insect and Disease

Forest tent caterpillar infestations occurred in 28 of out 99 watersheds and affected an average 35 percent of each watershed in the period 1998 to 2003 (range 0.1 percent to 159 percent). Insect outbreaks often reoccurred in a watershed. The Badou Lake catchment had forest tent caterpillar outbreaks in 1998, 1999 and 2000 which accumulated to over 100 percent of the watershed area. Outbreaks of forest tent caterpillar are primarily observed along the Bird, Manigotogan and Wanipigow river systems (Figure 7). Insect infestations appeared to parallel watercourses and developed areas. There were no observations north of the Wanipigow Lake watershed. Many of the effected watersheds have been subject to repeat disturbance.

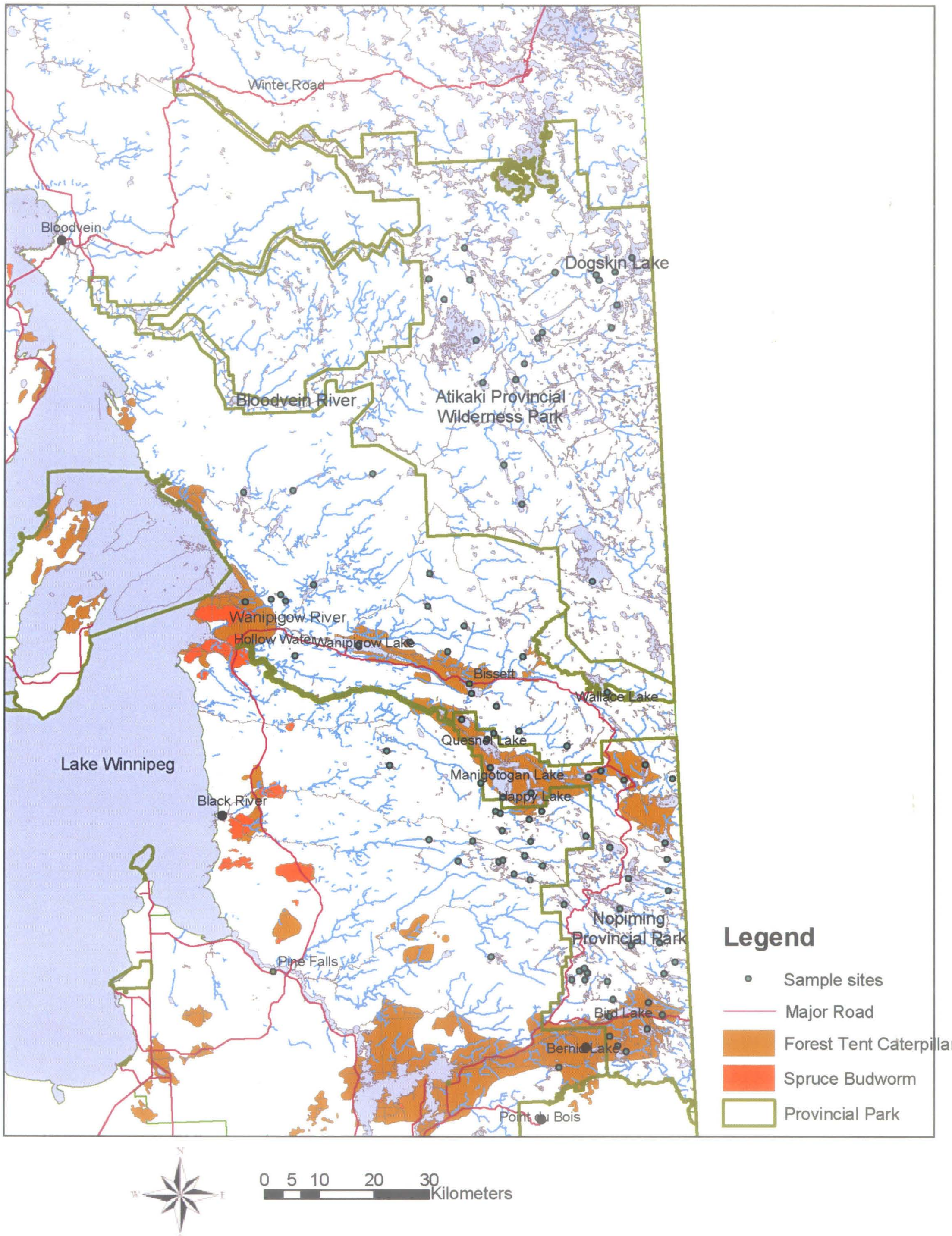

Figure 6: The distribution of spruce budworm and forest tent caterpillar infestation.

Forest tent caterpillar infestations appear along major river systems and developed areas. Data courtesy Tembec Industries –Pine Falls Operations.

With respect to spruce budworm, 26 watersheds have evidence of spruce budworm occurrence, affecting twelve percent of the watershed area on average (range <1% - 92%). Of the watersheds containing spruce budworm infestation, 23 out of 26 also harbor forest tent caterpillar populations. The average basal extent of insect damage from either spruce budworm, forest tent caterpillar or both, is 44 percent of the watershed area (<1 percent to 191 percent). Given the mean is highly affected by repeat insect infestations the median area of insect damage (24 percent) may be more meaningful.

4.1.3 Forest Harvesting

Though extensive watershed harvesting began in the 1950s, recent harvests (2002-2003) are concentrated north of Bird Lake, west of Happy Lake, north of Wanipigow Lake, in the Rainy Lake area, and Maskwa Lake (Figure 8). Most active forest harvesting is concentrated outside of Nopiming Provincial Park while no historical or active harvesting has occurred in Atikaki Wilderness Park.

Extensive river systems connect many lakes. Although these lakes may have active watershed harvesting in close proximity to the lakeshore, the relative proportion of the watershed disturbed in many cases is small. Generally, forest harvesting in the last five years has occurred in a relatively small area in each watershed. Recent forest harvesting has generally occurred in less than ten percent of the watershed area with the exception of harvesting north of Bird Lake in the Eastland Lake watershed (22 percent) and the Kinsley Lake watershed (13 percent). In contrast, in the last 35 years as much as 70 percent of the watershed area was logged for two watersheds (Blue Lake and Rush Lake) while seven watersheds experienced logging of approximately 50 percent of the catchment area (Table 9).

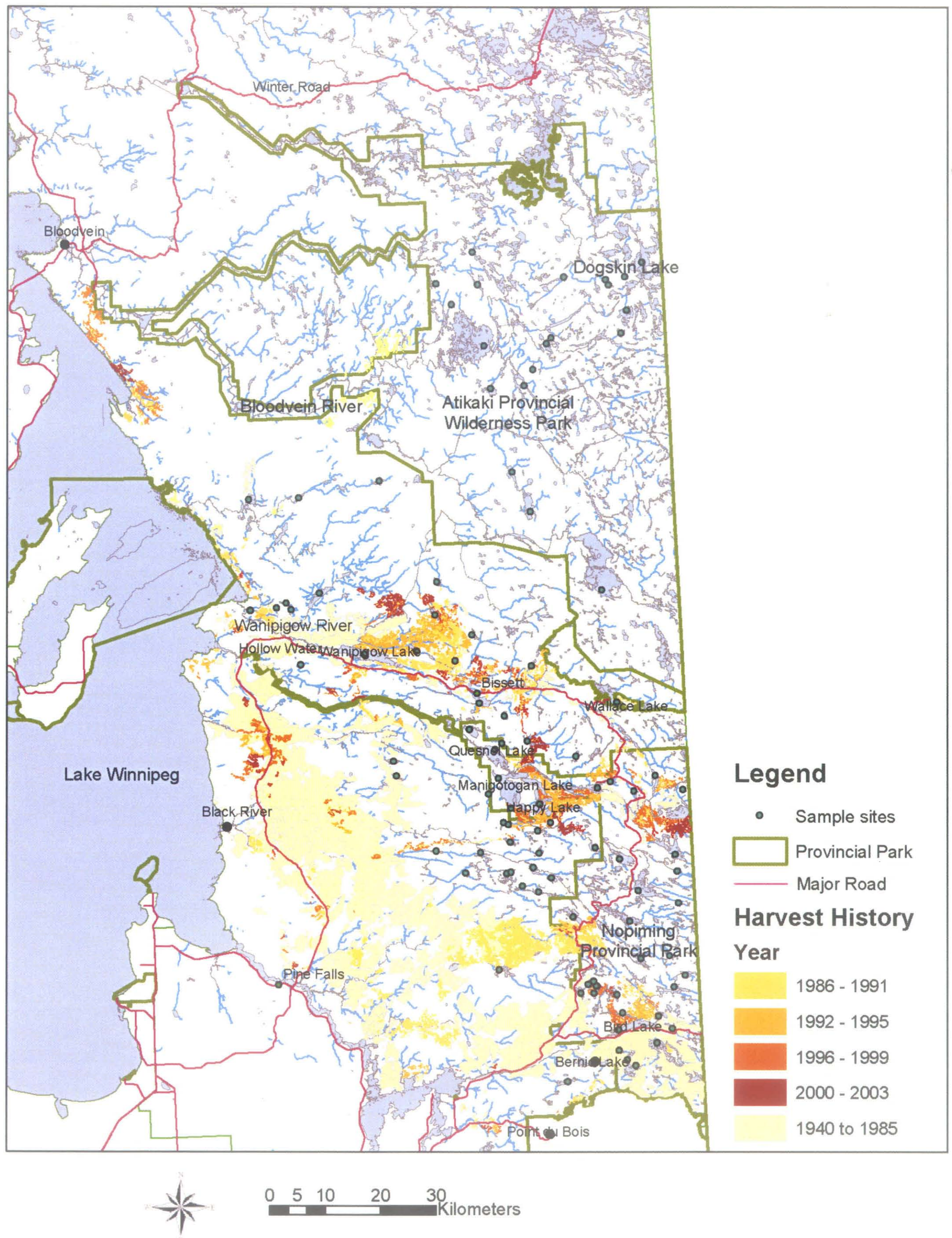

Figure 7: History of forest harvesting in the study area.

Most historical forest harvesting has occurred in the south and east portions of the study area while recent harvesting is concentrated nearer Nopiming Provincial Park. No forest harvesting has occurred in the Atikaki Wilderness Park. Data courtesy Tembec Industries- Pine Falls

Table 9: Cumulative proportion of the study watersheds disturbed by forest fire, forest harvesting in the last 5, 15, 35 and 50 years and insect disturbance (Forest Tent Caterpillars and Spruce Budworm) since 1995. Note: data was unavailable for watersheds originating in Ontario and these were removed from the analysis. Dashed line equals zero

		Forest Harvesting				Forest Fire				Insect Disturbance	
		Cumulative Percentage Harvested				Cumulative Percentage Burned				Tent	Budworm
Lake ID	Lake Name	Last 5	Last 15	Last 35	Last 50	Last 5	Last 15	Last 35	Last 50	Caterpillar	
3	Lincoln	-	-	-	-	-	-	-	-	-	-
4	Cole	1.3	1.5	1.9	1.9	-	-	-	-	-	-
5	Lapin	6.3	6.9	9.2	9.2	-	0.1	1.4	1.4	-	-
6	Unnamed	6.0	6.6	8.8	8.8	-	-	-	-	-	-
7	Metcalfe	-	-	-	-	-	-	-	-	-	-
8	Kinsley	12.5	12.5	15.7	15.7	-	-	-	-	-	-
9	Springer	8.2	8.2	16.5	16.5	-	-	19.2	19.2	-	-
14	Blue	-	-	60.7	60.7	-	-	-	-	99.4	92.4
15	Birse	-	-	36.3	36.3	-	0.0	0.0	1.5	64.1	27.2
16	Eastland	21.3	21.4	21.4	21.4	0.1	0.1	5.2	5.2	0.9	0.1
18	Glen lake	-	-	-	-	-	-	19.5	19.5	-	-
19	Terminal	-	-	-	-	-	0.0	22.6	-	-	-
20	Maskwa	-	8.1	14.4	29.4	0.0	2.4	41.5	43.1	-	-
21	Bernic	-	-	36.6	36.6	-	0.1	0.6	0.6	99.8	9.3
22	Shatford	-	-	-	-	-	-	0.1	0.1	37.4	16.4
23	Rush	-	-	66.6	66.6	-	-	0.0	0.0	91.5	32.3
24	Unnamed	11.9	11.9	11.9	11.9	-	-	51.2	51.2	-	-
25	Lost claim	-	-	-	-	-	-	-	-	-	-
26	Black	-	0.2	0.2	0.2	0.0	0.0	15.4	15.4	-	-
31	Tooth	-	-	-	-	-	-	71.1	71.1	-	-
35	Stormy	1.6	2.0	2.0	2.0	-	-	17.5	17.5	96.2	13.9
36	Badou	-	-	10.8	10.8	-	-	1.2	-	159.7	1.2
38	Unnamed	-	10.2	10.2	10.2	1.0	3.5	90.0	90.0	4.3	-
39	Big Clear Water	-	1.4	1.4	1.4	-	0.1	0.1	0.1	19.3	4.8

Lake ID	Lake Name	Forest Harvesting Cumulative Percentage Harvested Last 5	Last 15	Last 35	Last 50	Forest Fire Cumulative Percentage Burned Last 5	Last 15	Last 35	Last 50	Insect Disturbance Tent Caterpillar	Budworm
42	Unnamed	-	-	-	-	-	0.0	33.6	33.6	0.4	0.7
43	Unnamed	-	16.9	16.9	16.9	-	-	-	-	13.6	2.7
44	Happy	1.5	22.6	22.6	22.6	0.0	0.0	32.0	32.0	69.9	21.1
45	Spence	-	-	-	-	-	-	-	-	-	-
47	Wanipigow	1.4	5.9	10.0	10.0	0.1	2.5	40.8	40.8	9.2	12.6
48	Atiko	-	-	-	-	-	0.0	0.3	0.3	-	-
49	Unnamed	-	-	-	-	-	0.0	17.0	20.7	-	-
50	Shallow	-	0.1	0.5	0.5	0.0	8.1	13.4	22.5	-	-
51	English	1.3	1.3	2.2	2.2	0.0	26.1	34.5	34.8	-	-
52	Dawson	-	-	-	-	-	95.4	95.4	95.4	-	-
53	Boulette	-	-	-	-	-	95.4	95.4	95.4	-	-
56	Unnamed	-	-	-	-	-	100.0	100.0	100.0	-	-
57	Owl	-	-	23.6	23.6	-	1.5	1.5	24.2	-	5.8
58	Farrington	-	-	37.0	37.0	0.0	0.7	0.7	7.8	-	-
59	Unnamed	-	-	-	-	-	-	-	-	-	-
60	Unnamed	-	-	-	-	-	0.0	0.0	0.0	-	-
62	Unnamed	-	-	-	-	27.1	27.1	127.1	127.1	-	-
63	Unnamed	-	-	-	-	77.9	77.9	167.4	167.4	-	-
64	Unnamed	-	-	-	-	59.2	59.2	98.7	98.7	-	-
65	Manning	-	-	-	-	11.5	11.5	121.6	121.6	-	-
66	Unnamed	-	-	-	-	12.1	12.2	12.2	12.2	-	-
67	Unnamed	-	-	-	-	75.6	75.6	75.6	75.6	-	-
68	Unnamed	-	-	-	-	54.1	54.1	68.6	68.6	-	-
69	Gordon	-	-	-	-	-	0.0	1.2	1.2	-	-
70	Gilmour	-	1.2	1.2	1.2	0.0	1.1	1.2	1.2	-	-
71	Little Beaver	-	44.9	50.1	50.1	-	0.0	0.0	0.0	31.2	-
73	Gold	-	-	-	-	-	0.0	0.1	0.1	-	-

		Forest Harvesting				Forest Fire				Insect Disturbance	
		Cumulative Percentage Harvested				Cumulative Percentage Burned				Tent	Budwor
Lake ID	Lake Name	Last 5	Last 15	Last 35	Last 50	Last 5	Last 15	Last 35	Last 50	Caterpillar	m
74	Unnamed	4.2	4.2	4.2	4.2	-	0.1	24.6	24.6	-	-
76	Round	-	-	-	-	-	-	39.6	39.6	-	-
78	Unnamed	-	-	-	-	-	-	1.6	1.6	-	-
79	Unnamed	-	-	-	-	-	-	1.6	1.6	-	-
80	Unnamed	-	-	-	-	-	-	-	-	-	-
81	Unnamed	-	-	-	-	-	0.1	0.1	0.1	-	-
82	North Eagle	-	-	-	-	-	0.0	32.0	32.0	-	-
83	South Eagle	-	-	-	-	-	0.0	15.3	15.3	-	-
85	Hutt	0.3	5.0	5.0	5.0	0.0	0.1	11.0	11.2	-	-
86	Black River L	-	0.1	0.1	0.1	0.0	0.2	15.1	15.1	-	-
87	Brooks	-	-	-	-	-	-	58.5	58.5	-	-
88	Field	-	2.8	2.8	2.8	-	0.0	0.0	0.0	-	-
89	Unnamed	-	0.7	0.7	0.7	-	-	-	-	-	-
90	Unnamed	-	0.7	0.7	0.7	-	-	-	-	-	-
91	McRorie	-	-	-	-	-	0.0	0.0	0.0	-	-
92	West Rat	-	-	-	-	0.0	0.1	0.1	0.1	-	-
93	Peacock lake	-	-	-	-	-	-	-	-	-	-
94	Faraway	-	-	-	-	-	0.0	24.3	24.3	-	-
96	Unnamed	-	9.8	9.8	9.8	-	-	-	-	1.9	-
97	Unnamed	-	0.1	0.1	0.1	1.9	1.9	91.8	91.8	-	-
98	Kakaki	9.2	14.7	16.5	16.5	-	0.0	26.0	26.0	-	-
99	Okimaw	-	3.3	3.3	3.3	-	-	60.0	60.0	-	-
100	Saxton	0.9	34.0	49.1	49.1	0.6	1.3	5.2	5.2	1.2	10.8

4.1.4 Mechanical Site Preparation

Of the study watersheds, 18 have been subject to mechanical site preparation in support of silviculture operations. This may be higher if watersheds with origins in Ontario have been subject to site preparation. This has been accomplished predominantly through drag chains, disk trenching and shear blading. On average, mechanical site preparation in the last ten years has affected approximately three percent of the area of prepared watersheds. In the Saxton Lake watershed however, site preparation (disk trenching) between 1994 and 1999 occurred on approximately twelve percent of the watershed area (Figure 9).

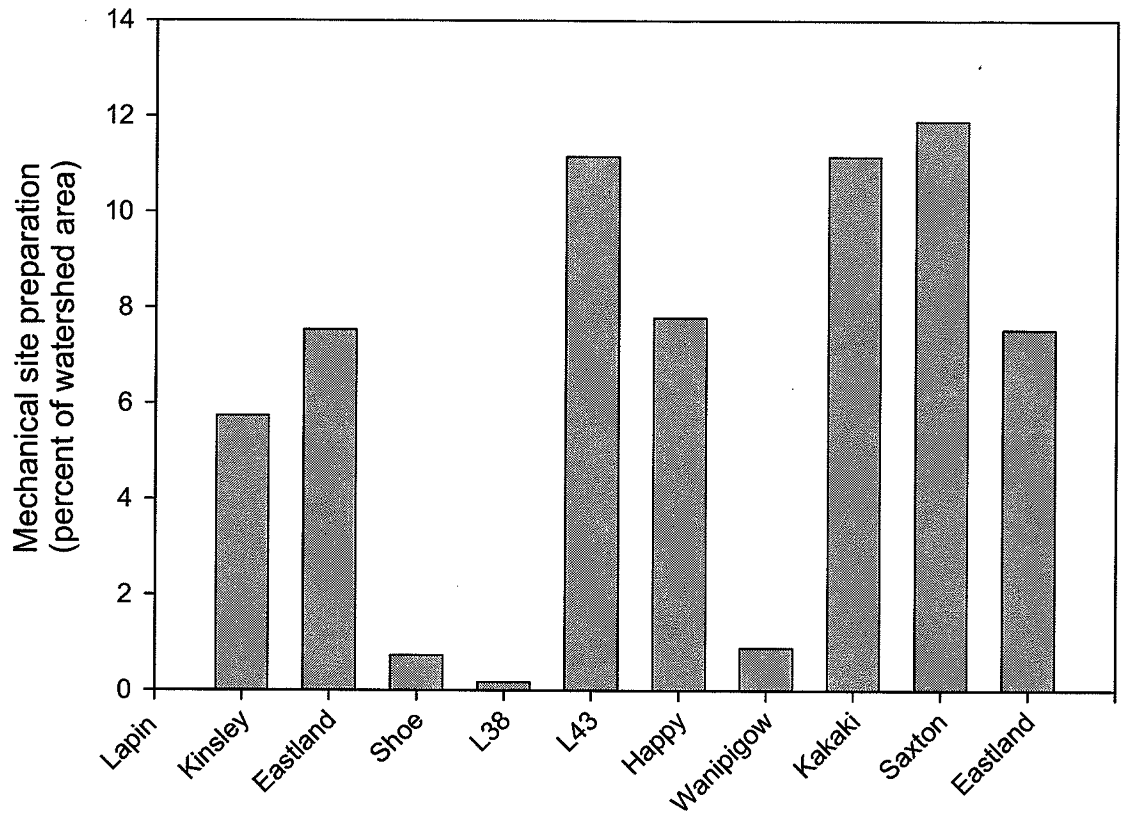

Figure 8: Lakes subject to mechanical site preparation and the proportion of the watershed treated

4.1.5 Combined Disturbance

Within the last 50 years, nine lakes have been subject to combined fire and harvest disturbance (Table 9). Currently, at least three watersheds historically burned within the last 50 years are being harvested. Okimaw Lake was subject to burning of 60 percent of its watershed since 1976 and the remaining older forest is currently being harvested. Maskwa Lake is another site subject to ongoing watershed harvesting. It was subject to harvesting and fire of 29 percent and 43 percent of the watershed area respectively since 1953. Happy Lake had harvesting of 22 percent of its watershed within the last 10 years and experienced burning of 32 percent of the watershed area within the last 20 years. Given that, active harvesting continues in the vicinity around Happy Lake, it is likely the proportion of the watershed harvested will continue to increase.

4.1.6 Grouping of Lakes

Lakes were categorized based on the disturbance history of their watersheds into reference (less than 15 percent of each fire or harvest) , harvested (over 15 percent of the watershed harvested within the last 50 years), burned (over 15 percent of the watershed burned over the last 50 years) and combined disturbance (both harvesting and forest fire combined to over 30 percent of the watershed area) categories. In total, there were 26 reference watersheds (Table 10), ten harvested watersheds (Table 12), 24 burned watersheds (Table 11) and nine lakes that had combined harvesting and fire disturbance in their watersheds (Table 13).

Table 10: Lakes with reference watersheds

(less than logging or fire 30% total disturbance since 1953) Harvesting data courtesy Tembec Industries- Pine Falls Operations.

Lake Id	Lake name	Percent Burned	Percent Harvested	Percent Total Disturbance
3	Lincoln	0.0	0.0	0.0
4	Cole	0.0	1.9	1.9
19	Terminal	0.0	0.0	0.0
22	Shatford	0.1	0.0	0.1
25	Lost claim	0.0	0.0	0.0
45	Spence	0.0	0.0	0.0
59	Unnamed	0.0	0.0	0.0
60	Unnamed	0.0	0.0	0.0
69	Gordon	1.2	0.0	1.2
70	Gilmour	1.2	1.2	2.4
73	Gold Lake	0.1	0.0	0.1
78	Unnamed	1.6	0.0	1.6
79	Unnamed	1.6	0.0	1.6
80	Unnamed	0.0	0.0	0.0
81	Unnamed	0.1	0.0	0.1
85	Hutt	11.2	5.0	16.2
86	Black River	15.1	0.1	15.2
88	Field	0.0	2.8	2.9
89	Unnamed	0.0	0.7	0.7
90	Unnamed	0.0	0.7	0.7
91	McRorie	0.0	0.0	0.0
92	West Rat	0.1	0.0	0.1
93	Peacock lake	0.0	0.0	0.0
36	Badou	0.0	10.8	10.8
96	Unnamed	0.0	9.8	9.8
66	Unnamed	12.2	0.0	12.2

Table 11: Lakes with burned watersheds

(greater than 15% watershed fire since 1953) Note: values over 100 percent are due to multiple burns in each watershed

Lake Id	Lake name	Percent Burned	Percent Harvested	Percent Total Disturbance
31	Tooth	71.1	0.0	71.1
42	Unnamed	33.6	0.0	33.6
50	Shallow	22.5	0.5	23.0
51	English	34.8	2.2	37.0
52	Dawson	95.4	0.0	95.4
53	Boulette	95.4	0.0	95.4
56	Unnamed	100.0	0.0	100.0
62	Unnamed	127.1	0.0	127.1
63	Unnamed	167.4	0.0	167.4
64	Unnamed	98.7	0.0	98.7
67	Unnamed	75.6	0.0	75.6
68	Unnamed	68.6	0.0	68.6
74	Unnamed	24.6	4.2	28.7
76	Round	39.6	0.0	39.6
82	North Eagle	32.0	0.0	32.0
83	South Eagle	15.3	0.0	15.3
87	Brooks	58.5	0.0	58.5
94	Faraway	24.3	0.0	24.3
97	Unnamed	91.8	0.1	91.9
18	Glen lake	19.5	0.0	19.5
26	Black	15.4	0.2	15.6
35	Stormy	17.5	2.0	19.5
65	Manning lake	121.6	0.0	121.6

Table 12: Lakes with harvested watersheds

(greater than 15% of the watershed disturbed by forest harvesting since 1953)

Lake Id	Lake name	Percent Burned	Percent Harvested	Percent Total Disturbance
8	Kinsley	0.0	15.7	15.7
14	Blue	0.0	60.7	60.7
15	Birse	1.5	36.3	37.8
16	Eastland	5.2	21.4	26.5
21	Bernic	0.6	36.6	37.2
23	Rush	0.0	66.6	66.6
43	Unnamed	0.0	16.9	16.9
58	Farrington	7.8	37.0	44.8
71	Little Beaver	0.0	50.1	50.1
100	Saxton	5.2	49.1	54.3

Table 13: Lakes with both harvested and burned watersheds (greater than 30% total disturbance since 1953)

Lake Id	Lake name	Percent Burned	Percent Harvested	Percent Total Disturbance
9	Springer	19.2	16.5	35.7
20	Maskwa	43.1	29.4	72.5
24	Unnamed	51.2	11.9	63.1
38	Unnamed	91.0	10.2	101.2
44	Happy	32.0	22.6	54.6
47	Wanipigow	40.8	10.0	50.8
57	Owl	24.2	23.6	47.8
98	Kakaki	26.0	16.5	42.5
99	Okimaw	60.0	3.3	63.4

On average, reference watersheds had 2.5 percent total disturbance (range 0 to 16 percent) split evenly between harvesting and fire disturbance. Burned watersheds had on average 63.5 percent total disturbance (range 15.6 to 167 percent). Harvested watersheds had 39 percent harvest disturbance and 41 percent total disturbance (range 15.7 to 66.6 percent). Lakes with both watershed harvesting and watershed fire had an average total disturbance of 59.1 percent (range 35.7 to 101.2 percent).

4.1.7 Soils

Soils of this region are typical of the Canadian Shield ecozone and are dominated by granitic bedrock. The majority of watersheds are dominated by acidic bedrock (BR/R2). Due to missing data for Ontario the watersheds from Ontario had to be excluded from the soils analysis. In fact, only 5 of 74 watersheds not originating in Ontario are not dominated by bedrock soil. These included Okimaw Lake, Lake 96, Gold Lake and the Dawson and Boulette watersheds (Table 15).

The watershed soil composition of Dawson, Boulette, Gold Lake and Lake 96 is dominated by deep basin acidic bedrock (DB/R2). The Okimaw Lake watershed was dominated by organic deposit acidic rock (OD/R2).

Soil conditions observed in the study area also included gaciofluvial deposit acid hard rock (GD/R2) and glacial till, resulting from Precambrian rock/ acidic hard rock (T3) though these categories never exceeded four percent of any watershed.

The north and east of the study area are dominated by acidic bedrock. Further west towards the shores of Lake Winnipeg and south west of the study area, an increased prevalence of deep basin and organic soils becomes evident. In the Wanipigow lake region, a band of deep basin soil extends from south of Wanipigow lake to Lake Winnipeg (Figure 10).

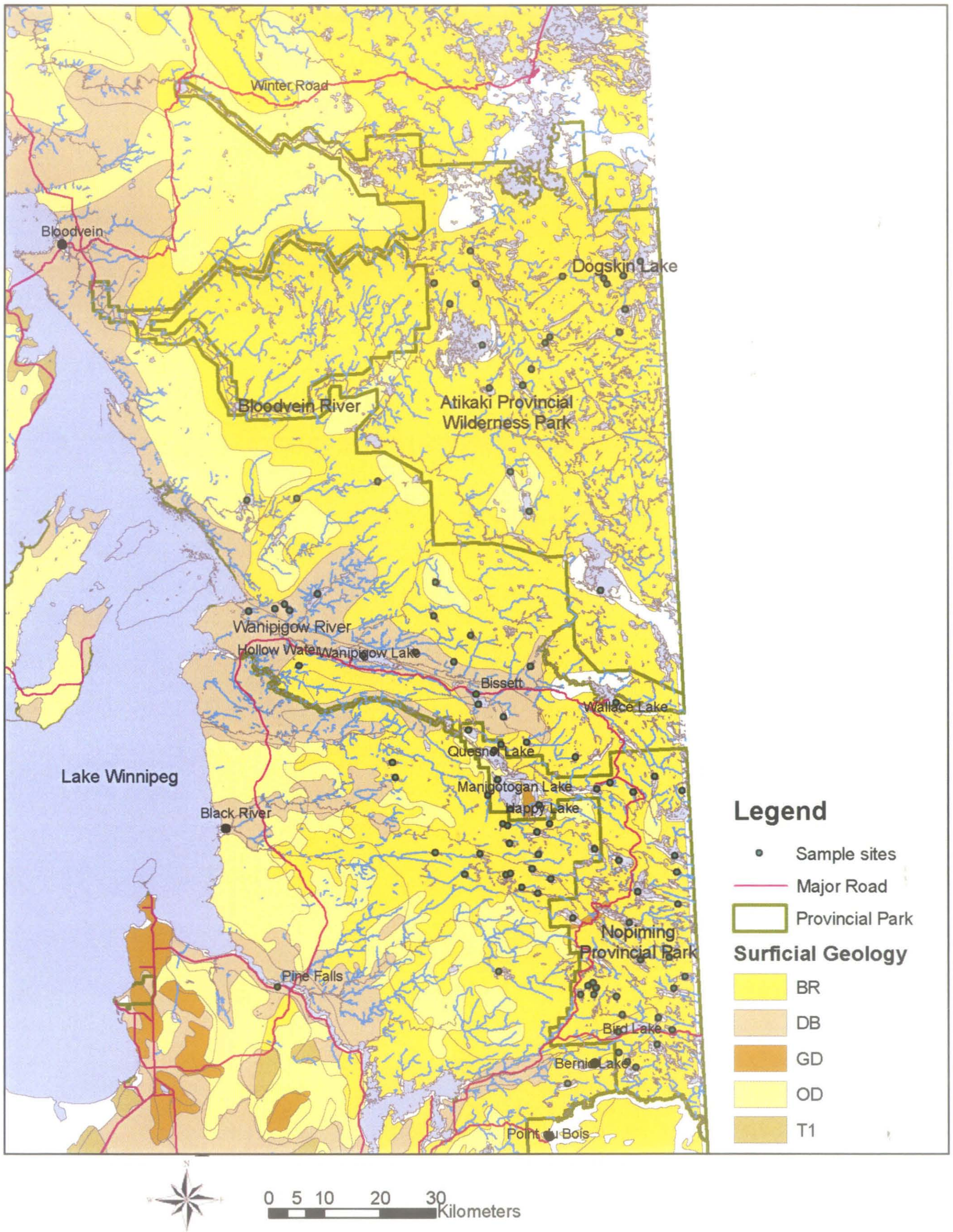

Figure 9: Distribution of soils in the study area

BR= bedrock dominated soils, DB= Deep Basin Soils, GD=glaciofluvial deposit/ acidic hard rock, OD= Organic Deposits, T3=glacial till derived from Precambrian rock. Soils data from the Manitoba Enduring Features Database

4.1.8 Forest Resource Inventory

The majority of the watersheds are dominated by coniferous species (jack pine, black spruce). On average, jack pine occupied 46 percent of the study watersheds. However, this was 88 percent for L38. Black spruce ranged in abundance from an average of 9 percent to a high of 46 percent of a watershed area (Table 14).

4.1.9 Wetlands

The non productive categories from the Forest Resource Inventory, (Muskeg, Treed Muskeg, Beaver Flood, Marsh and Willow Alder) were merged, producing a measurement of the total percentage of wetlands in each watershed. On average, wetlands of this type occupied 19 percent of the watershed area (Table 14). This ranged from 1.1 percent for Lake 38 to 43 percent for the Okimaw Lake watershed. Reference lakes on average had the lowest wetland percentage at 13 percent. Watersheds with fires older than 15 years and harvested watersheds had the highest proportion of wetlands at 21 and 20 percent respectively.

4.1.10 Linear Features

Linear features within each watershed include roads, power lines and trails. The density of linear features (km/km^2 of watershed) was calculated. Excluded from the analysis were watersheds with origins in Ontario and regenerated roads. Only 38 of the 73 watersheds analyzed contained any linear features (Table 15). The Wanipigow Lake watershed had the highest length of linear features (448 km) however, it had a low density (i.e, linear feature length to total watershed area of 0.32 km road / km^2 of watershed area. Mean length of linear features in watersheds where they occurred was 27 km. The highest road density occurred in the smallest watersheds. Lake 38, Lapin Lake and Lake 87 watersheds had the highest density of linear features at 2.8, 2.4 and 2.3 km / km^2 watershed area. It is not surprising that these watersheds were recently subject to forest harvesting. No watersheds within Atikaki Wilderness Park contained any linear features. In terms of total area, roads were by far the most dominant of the linear features. Class 4 (Winter Access Roads) were the dominant road type.

4.2 Physical Characteristics of the Lakes

4.2.1 Watershed Size

Watershed size for the 99 lakes ranged from 64 hectares to over 200,000 hectares (Table 16), the largest watershed being the Aikins Lake watershed and the smallest being the Peacock Lake watershed. The average watershed size for the lakes sampled in 2004 was 16,300 hectares and 1,580 hectares for 2005. Many of the larger watersheds have origins in Ontario. Lakes with small or limited inflowing tributaries generally had the smallest watershed areas. Lakes with many inflowing tributaries had the largest watershed areas and largest drainage ratios (Table 17). Watersheds of lakes sampled in 2005 ranged in size from 193 hectares to 6,700 hectares (Table 18). Median watershed size in 2005 was 925 hectares. Sampling in 2005 focused on smaller headwater lakes which typically had smaller watersheds.

Table 14: Percentage of various landscape features in the study watersheds. Soil type BR= bedrock, DB= deep basin, OD = organic deposits, GD= gaciofluvial depoist acid hard rock, T3 =Glacial till derived from acidic bedrock. Note: Proportion of Wetland, Jackpine, Black Spruce, Hardwoods, Treed Rock and Water obtained from the Manitoba Forest Resource Inventory (1983 and 1997) Soils data obtained from the enduring features database developed by the World Wildlife Fund (1997). Data was unavailable for watersheds originating in Ontario and these were excluded from the analysis. ND= no data. Dashed line equals

Lake ID	Lake Name	Wetland	Jack Pine	Black Spruce	Hardwoods	Treed Rock	Water	BR	DB	OD	Soil Type GD	T3
3	Lincoln	11.7	59.3	25.5	2.4	-	13.9	100.0	-	-	-	-
4	Cole	12.2	66.9	9.8	1.6	0.2	13.1	93.0	-	-	-	-
5	Lapin	21.6	56.9	11.0	0.1	2.0	16.4	100.0	-	-	-	-
6	unnamed	20.1	53.2	-	0.1	1.9	15.3	95.8	-	-	-	-
7	Metcalfe	19.6	51.8	-	0.1	1.8	14.9	95.8	-	-	-	-
8	Kinsley	31.2	47.8	3.1	5.6	-	20.2	100.0	-	-	-	-
9	Springer	27.2	46.8	3.1	6.7	0.3	21.2	92.0	-	-	-	-
14	Blue	4.9	33.9	6.4	29.6	1.8	15.6	100.0	-	-	-	-
15	Birse	13.1	44.2	5.9	32.7	0.5	29.7	75.5	-	-	-	-
16	Eastland	16.9	70.7	4.0	-	1.1	9.6	100.0	-	-	-	-
18	Glen lake	15.3	63.9	14.6	-	5.9	41.8	100.0	-	-	-	-
19	Terminal	26.8	47.6	17.2	1.5	3.3	7.8	100.0	-	-	-	-
20	Maskwa	25.9	45.7	10.9	9.4	1.7	3.1	69.3	-	29.3	-	-
21	Bernic	11.4	43.0	13.2	10.2	1.7	17.3	82.7	-	-	-	-
22	Shatford	27.9	47.8	3.4	11.0	2.2	10.3	92.8	-	-	-	-
23	Rush	12.5	27.3	9.2	26.2	3.9	13.6	100.0	-	-	-	-
24	unnamed	36.6	60.5	1.4	1.3	-	13.7	100.0	-	-	-	-
25	Lost claim	4.9	80.7	6.1	-	-	22.1	79.0	-	-	-	-
26	Black	17.8	60.8	9.4	1.4	0.4	12.5	90.6	-	-	3.2	-
31	Tooth	14.6	63.0	6.5	4.0	2.0	40.0	74.8	-	-	-	-
35	Stormy	17.0	49.4	14.7	14.1	0.1	5.8	100.0	-	-	-	-
36	Badou	14.1	30.8	15.8	35.4	-	6.7	100.0	-	-	-	-
38	unnamed	1.3	87.8	1.9	0.1	5.7	24.5	100.0	-	-	-	-

								Soil Type				
Lake ID	Lake Name	Wetland	Jack Pine	Black Spruce	Hardwoods	Treed Rock	Water	BR	DB	OD	GD	T3
39	Big Clear Water	23.7	55.4	8.0	4.4	3.7	15.9	73.0	16.6	-	-	-
42	unnamed	29.8	50.0	10.8	1.2	6.1	2.9	93.1	-	6.9	-	-
43	unnamed	33.2	32.6	8.2	4.9	3.9	9.9	97.4	-	-	-	-
44	Happy	19.0	35.7	12.7	23.4	1.0	14.3	54.7	-	31.4	4.6	-
45	Spence	26.1	62.3	6.0	1.4	2.6	6.1	100.0	-	-	-	-
47	Wanipigow	22.5	41.1	7.6	11.1	1.1	5.4	62.6	14.5	3.5	-	3.7
48	Atiko	26.7	59.2	4.4	0.2	0.5	4.7	83.1	-	16.9	-	-
49	unnamed	38.1	48.1	3.9	2.3	3.6	2.4	84.3	-	15.7	-	-
50	Shallow	38.0	45.7	6.8	2.1	4.2	2.6	62.0	-	34.2	-	-
51	English	30.2	47.5	6.4	8.9	1.1	2.7	57.3	40.5	0.1	-	-
52	Dawson	30.1	22.2	5.2	29.5	5.6	10.3	19.3	80.7	-	-	-
53	Boulette	30.4	22.3	5.2	29.7	5.6	10.4	-	-	-	-	-
56	unnamed	21.8	28.5	1.8	38.5	-	6.3	100.0	-	-	-	-
57	Owl	31.4	46.3	14.9	3.1	1.0	6.4	97.5	2.5	-	-	-
58	Farrington	27.1	39.4	13.9	14.7	0.5	9.9	92.5	1.3	6.2	-	-
59	unnamed	20.5	62.5	1.1	58.4	9.5	-	100.0	-	-	-	-
60	unnamed	13.2	65.0	9.0	85.3	4.6	17.0	100.0	-	-	-	-
62	unnamed	14.6	64.2	6.0	37.0	13.5	817.6	100.0	-	-	-	-
63	unnamed	34.6	59.7	1.7	47.1	4.0	9.3	100.0	-	-	-	-
64	unnamed	11.6	88.2	-	25.1	-	14.3	100.0	-	-	-	-
65	Manning	25.3	74.7	0.0	41.2	-	16.5	100.0	-	-	-	-
66	unnamed	16.7	55.9	3.5	38.9	5.2	0.3	88.9	-	-	-	-
67	unnamed	7.2	62.1	13.7	55.7	8.5	587.6	100.0	-	-	-	-
68	unnamed	18.7	33.6	25.2	46.5	21.5	22.5	100.0	-	-	-	-
69	Gordon	9.4	34.0	34.6	1.0	9.0	28.6	100.0	-	-	-	-
70	Gilmour	21.3	43.6	17.0	0.4	10.6	8.3	100.0	-	-	-	-
71	Little Beaver	16.6	21.6	22.9	37.0	-	6.0	62.8	37.2	-	-	-

Lake ID	Lake Name	Wetland	Jack Pine	Black Spruce	Hardwoods	Treed Rock	Water	BR	DB	OD	GD	T3
											Soil Type	
73	Gold	33.9	52.3	9.7	0.3	0.4	8.2	-	93.4	-	-	-
74	unnamed	30.1	58.5	6.5	0.4	0.0	3.2	91.3	8.7	-	-	-
76	Round	13.7	59.5	6.9	45.5	10.5	-	86.6	-	-	-	-
78	unnamed	ND	ND	ND	ND	ND	ND	92.6	-	-	-	-
79	unnamed	ND	ND	ND	ND	ND	ND	83.5	-	-	-	-
80	unnamed	26.7	59.1	0.4	27.1	11.5	1.5	100.0	-	-	-	-
81	unnamed	22.1	76.0	-	35.4	1.2	37.2	100.0	-	-	-	-
82	North Eagle	21.0	37.4	6.2	51.3	7.9	-	49.1	-	39.7	-	-
83	South Eagle	16.2	44.0	9.6	51.4	3.8	22.9	48.2	-	37.6	-	-
85	Hutt	23.8	47.4	13.2	1.1	4.0	9.3	88.0	-	1.4	4.2	-
86	Black River L	17.6	56.8	10.1	1.3	1.1	12.4	92.8	-	-	2.3	-
87	Brooks	16.0	73.0	4.9	0.0	-	12.5	100.0	-	-	-	-
88	Field	27.6	39.0	16.7	0.0	11.8	13.0	100.0	-	-	-	-
89	unnamed	ND	ND	ND	ND	ND	ND	100.0	-	-	-	-
90	unnamed	24.5	53.3	6.1	1.1	9.5	6.4	100.0	-	-	-	-
91	McRorie	16.3	47.0	12.3	0.1	13.5	16.4	100.0	-	-	-	-
92	West Rat	20.9	61.9	10.8	0.6	2.7	7.3	100.0	-	-	-	-
93	Peacock lake	4.6	33.6	45.8	-	12.9	29.4	100.0	-	-	-	-
94	Faraway	27.5	67.6	2.0	-	0.1	7.1	100.0	-	-	-	-
96	unnamed	13.9	49.5	24.1	12.1	-	14.4	6.0	86.4	-	-	-
97	unnamed	24.2	59.7	11.3	1.0	-	12.0	87.6	-	-	-	-
98	Kakaki	28.8	32.5	32.5	1.5	0.6	3.0	70.9	-	26.8	-	-
99	Okimaw	43.3	45.2	16.3	-	0.5	4.3	19.8	-	75.4	-	-
100	Saxton	15.0	27.8	17.7	32.9	1.5	3.3	57.4	42.6	-	-	-
Min		1.3	21.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean		21.3	51.0	10.0	15.6	3.6	31.7	84.4	5.7	4.4	0.2	0.0
Median		21.0	49.5	8.0	4.4	1.8	10.4	95.8	0.0	0.0	0.0	0.0
Max		43.3	88.2	45.8	85.3	21.5	817.6	100.0	93.4	75.4	4.6	3.7

Table 5 : Total Length and proportion of linear features in the study watersheds. Linear features include: acccess roads, trails, powerlines and highways. Dashed line = there were no linear features in the watershed

Lake ID	Lake Name	Total length of linear features (km)	Proportion linear features in the watershed ( )
3	Lincoln	-	-
4	Cole	-	-
5	Lapin	22.1	2.4
6	unnamed	-	-
7	Metcalfe	-	-
8	Kinsley	8.7	0.9
9	Springer	12.5	0.9
14	Blue	-	-
15	Birse	2.5	0.2
16	Eastland	20.8	1.9
18	Glen lake	-	-
19	Terminal	-	-
20	Maskwa	42.3	0.2
21	Bernic	7.3	0.3
22	Shatford	7.1	0.2
23	Rush	3.9	0.3
24	unnamed	2.4	1.3
25	Lost claim	-	-
26	Black	25.2	0.1
31	Tooth	16.3	0.7
35	Stormy	12.8	0.8
36	Badou	6.9	1.3
38	unnamed	3.2	2.8
39	Big Clear Water	-	-
42	unnamed	-	-
43	unnamed	6.3	1.4
44	Happy	28.0	0.6
45	Spence	10.5	1.3
47	Wanipigow	448.4	0.3
48	Atiko	-	-
49	unnamed	-	-
50	Shallow	42.5	0.1
51	English	39.3	0.2
52	Dawson	4.2	0.3
53	Boulette	-	-
56	unnamed	-	-
57	Owl	3.2	0.1

Lk D Lk Nm e	Tal legh linarfeats (km)	Pinar feat tin watershd)
58 Farrington	-	-
59 unnamed	-	-
60 unnamed	-	-
62 unnamed	-	-
63 unnamed	-	-
64 unnamed	-	-
65 Manning	-	-
66 unnamed	-	-
67 unnamed	-	-
68 unnamed	-	-
69 Gordon	6.7	0.6
70 Gilmour	5.6	0.2
71 Little Beaver	2.9	0.5
73 Gold	22.5	1.8
74 unnamed	31.0	0.5
76 Round	-	-
78 unnamed	-	-
79 unnamed	-	-
80 unnamed	-	-
81 unnamed	-	-
82 North Eagle	-	-
83 South Eagle	-	-
85 Hutt	15.7	0.2
86 Black River L	30.0	0.1
87 Brooks	11.1	2.3
88 Field	14.1	1.1
89 unnamed	-	-
90 unnamed	2.3	0.3
91 McRorie	-	-
92 West Rat	-	-
93 Peacock lake	-	-
94 Faraway	2.8	0.3
96 unnamed	2.2	0.3
97 unnamed	-	-
98 Kakaki	51.0	1.0
99 Okimaw	6.1	0.3
100 Saxton	47.5	0.8

Table 16: Catchment characteristics of 99 boreal lakes sampled in 2004

Watershed areas were obtained from 1:50,000 topographic maps. **Note 1:** Latitude and Longitude in decimal degrees. **2:** Depth at sample site (sampling generally occurred at the deepest location in each lake) 3: Shoreline Development calculated for each lake based on the formula of Hutchinson (1957).

LAKE ID	LAKE NAME	Lake area (ha)	Shoreline Development	Max length (m)	Watershed area (ha)	Drainage Ratio	Depth at sample site (m)
1	Elbow lake	427	4.31	4,300	83,376	195.5	11.7
2	MacGregor	201	3.58	1,200	83,601	415.2	12.2
3	Lincoln	65	2.97	1,600	505	7.8	3.9
4	Cole	266	6.04	2,700	4,213	15.9	4.2
5	Lapin	71	2.57	900	867	12.1	1.7
6	unnamed	52	2.64	1,250	928	18.0	3.2
7	Metcalf	26	2.23	1,200	953	36.4	3.5
8	Kinsley	81	3.93	1,500	898	11.1	2.8
9	Springer	99	3.70	1,450	1,373	13.8	4.4
10	Bird	744	3.67	6,900	103,234	138.8	8.1
11	Tulibi	156	2.40	1,700	8,790	56.2	12.9
12	Starr	105	2.59	1,600	4,586	43.7	2.2
13	Booster	620	4.07	3,200	6,126	9.9	7.1
14	Blue	26	1.83	715	165	6.4	3.3
15	Birse	315	3.16	2,500	1,124	3.6	10.0
16	Eastland	57	3.09	1,500	1,048	18.5	3.9
18	Glen lake	109	2.85	1,800	261	2.4	5.9
19	Terminal	142	5.45	4,000	2,356	16.6	9.2
20	Maskwa	244	4.09	2,300	22,372	91.7	1.2
21	Bernic	382	5.00	3,128	2,433	6.4	7.0
22	Shatford	220	3.72	3,300	3,422	15.6	2.2
23	Rush	36	1.82	1,400	1,104	31.0	3.8
24	unnamed	21	2.29	700	157	7.3	2.1
25	Lost Claim	75	2.92	1,700	429	5.7	12.9

26	Black	633	7.44	3,700	16,721	26.4	6.1
27	Shoe	471	3.20	3,800	2,507	5.3	7.3
29	Slate	46	6.83	1,400	15,429	336.9	1.7
30	Gem	871	1.98	6,900	32,238	37.0	13.2
31	Tooth	598	5.96	3,400	1,864	3.1	14.9
28	Flintstone	1,078	4.70	5,300	12,365	11.5	8.9
32	Moose	199	9.56	1,800	20,329	102.0	4.8
33	unnamed	42	1.43	930	165	3.9	1.0
34	Beresford	284	3.43	2,600	22,447	79.1	4.0
35	Stormy	62	2.25	1,950	1,562	25.4	5.0
36	Badou	33	1.76	1,500	493	15.0	4.5
37	Long	761	7.35	5,200	49,164	64.6	2.4
38	unnamed	23	1.74	670	92	4.1	6.9
39	Big Clear Water	351	2.66	3,000	2,708	7.7	15.0
40	Quesnel	991	5.09	4,100	115,245	116.3	13.1
41	Manigotogan	2,461	5.06	6,000	143,340	58.2	9.0
42	unnamed	54	3.47	700	2,317	43.1	2.2
43	unnamed	40	1.50	1,000	405	10.1	0.8
44	Happy	458	3.99	2,700	4,204	9.2	8.4
45	Spence	38	2.54	1,300	768	20.3	3.2
46	Frenchman	108	3.03	3,200	27,014	251.3	8.9
54	unnamed	11	6.62	485	64	5.7	3.4
50	Shallow	421	2.46	2,400	56,307	133.7	1.5
55	Clangula	52	2.93	940	160,000	3051.8	2.1
47	Wanipigow	1,821	4.07	10,000	140,149	77.0	4.2
49	unnamed	80	4.44	2,000	12,114	152.0	5.3
48	Atiko	94	2.24	2,400	2,208	23.4	17.4
51	English	499	3.35	5,400	25,587	51.3	11.7
52	Dawson	53	1.20	1,000	1,256	23.5	7.3
53	Boulette	63	1.46	1,500	1,246	19.9	5.5
58	Farrington	105	1.75	2,200	1,242	11.8	3.0
56	unnamed	23	3.19	970	374	16.0	4.3
57	Owl	124	2.65	2,600	2,121	17.1	2.8

59	unnamed	132	2.70	1,500	477	3.6	5.9
60	unnamed	504	3.60	2,800	778	1.5	4.5
61	Dogskin	3,534	7.09	4,600	58,836	16.6	8.3
62	unnamed	37	1.84	1,000	523	14.0	3.4
63	unnamed	34	1.78	1,100	401	11.7	2.9
64	unnamed	32	2.10	1,300	240	7.5	2.4
65	Manning	31	2.47	1,300	193	6.3	3.4
66	unnamed	277	4.52	2,100	10,858	39.2	3
67	unnamed	87	2.50	1,500	269	3.1	2.9
68	unnamed	26	1.95	750	478	18.6	3
69	Gordon	198	6.98	850	934	4.7	7.7
73	Gold	93	2.60	1,300	1,158	12.4	1
74	unnamed	10	1.43	680	6,665	635.4	1.4
70	Gilmour	49	2.72	2,200	2,848	58.2	2.6
71	Little Beaver	33	2.22	780	545	16.7	6.8
72	Rice	434	1.72	3,450	7,258	16.7	3.2
75	Kawaseecheewonk	1,268	5.83	4,900	49,186	38.8	9.9
76	Round	258	2.80	2,450	1,787	6.9	5.8
77	Sasaginnigak	4,395	9.85	6,000	109,362	24.9	8.4
78	unnamed	133	3.79	2,630	1,070	8.1	8.2
79	unnamed	41	1.72	1,100	896	21.9	21.4
80	unnamed	100	4.30	1,600	1,098	10.9	9.3
81	unnamed	32	2.19	850	270	8.5	13.3
82	North Eagle	276	2.45	4,600	9,762	35.4	1.5
83	South Eagle	664	3.57	4,800	4,949	7.5	4.9
84	Aikins	2,222	8.32	6,240	212,241	95.5	24.8
85	Hutt	54	3.82	1,900	8,281	152.3	2.2
86	Black River Lake	162	9.49	1,700	24,696	152.9	5.9
87	Brooks	34	2.01	1,000	452	13.3	6.9
88	Field	130	4.73	2,100	1,130	8.7	4.1
89	unnamed	16	1.71	550	727	45.6	7.9
90	unnamed	20	1.76	760	723	36.1	8.0
91	McRorie	73	4.17	1,900	1,127	15.5	4.8

92	West Rat	35	3.03	800	736	20.8	2
93	Peacock	19	1.80	600	64	3.4	5.5
94	Faraway	50	4.25	1,100	1,015	20.2	2.4
95	Wallace	1,068	5.41	5,600	18,903	17.7	6.1
96	unnamed	96	2.78	1,600	668	7.0	3
97	unnamed	73	4.23	1,400	717	9.9	3.1
98	Kakaki	92	3.57	1,300	5,005	54.3	2.5
99	Okimaw	123	2.91	2,400	2,121	17.2	8.5
100	Saxton	106	2.10	1,700	5,899	55.4	3

Table 17: Lakes sampled in 2005

Watershed areas were obtained from 1:50,000 topographic maps. Average depth obtained from transects across each lake in May, August and September 2005. Areas are in hectares. Length in meters. DR = drainage ratio

LAKE_ID	LAKE_NAME	Lake area (ha)	Max length (m)	Watershed area	DR	Depth at sample site (m)	Average Depth (m)
7	Metcalf	26.2	1,200	953.0	36.4	3.5	3.1
8	Kinsley	81.2	1,500	898.0	11.1	2.8	2.9
9	Springer	99.1	1,450	1372.8	13.8	4.4	4.9
16	Eastland	56.7	1,500	1048.2	18.5	3.9	4.1
18	Glen lake	109.3	1,800	261.4	2.4	5.9	5.3
19	Terminal	142.3	4,000	2356.3	16.6	9.2	5.7
43	unnamed	39.9	1,000	405.0	10.1	0.8	1.8
44	Happy	457.6	2,700	4204.3	9.2	8.4	9.2
45	Spence	37.8	1,300	767.6	20.3	3.2	2.4
53	Boulette	62.7	1,500	1246.5	19.9	5.5	4.2
58	Farrington	105.1	2,200	1241.9	11.8	3	2.1
57	Owl	124.1	2,600	2120.6	17.1	2.8	2.6
59	unnamed	132.3	1,500	476.9	3.6	5.9	4.8
60	unnamed	504.3	2,800	777.7	1.5	4.5	3.5
63	unnamed	34.2	1,100	401.0	11.7	2.9	3.3
64	unnamed	32.0	1,300	239.7	7.5	2.4	2.9
65	Manning lake	30.8	1,300	193.5	6.3	3.4	4.6
67	unnamed	87.2	1,500	268.5	3.1	2.9	3.3
68	unnamed	25.6	750	478.0	18.6	3	3.1
74	unnamed	10.5	680	6665.1		1.4	2.1
76	Round	258.1	2,450	1787.3	6.9	5.8	6.2
80	unnamed	100.5	1,600	1097.6	10.9	9.3	8.2
87	Brooks	34.0	1,000	451.8	13.3	6.9	14.9
92	West Rat	35.4	800	736.0	20.8	2	4.0

97	unnamed	72.6	1,400	716.6	9.9	3.1	3.4
98	Kakaki	92.3	1,300	5005.3	54.3	2.5	3.1
99	Okimaw	123.3	2,400	2121.1	17.2	8.5	6.0
100	Saxton	106.4	1,700	5898.6	55.4	3	2.9

4.2.2 Lake Area

Lakes sampled in 2004 represented a large range of lake sizes, depths and characteristics (headwater lakes versus lakes on major river systems). Lakes ranged from shallow wetlands to deep meteor impact lakes. The goal in 2004 was to gain an understanding of baseline conditions in a wide cross section of lake types. Time constraints and the size of some lakes made detailed depth sounding beyond the scope of this work. Lake size in 2004 ranged from 10.5 hectares to 4395 hectares. In 2005, lake size ranged from 10.5 hectares to 504 hectares. Average lake size was 106 hectares in 2005 and 349 hectares in 2004 (this was result of the focus on smaller headwater lakes in 2005).

4.2.3 Watershed to Lake Area Ratio

The watershed to lake area ratio or drainage ratio is typically an indication of the flushing/ renewal time of a water body. It is expected that lakes with high drainage ratios will be more sensitive to disturbance in the watershed. Drainage ratios in 2004 ranged from 1.5 to 3051 (Table 16) where high ratios were associated with lakes on or downstream of a large river system. The mean DR for the study area was 78.3. The median DR was 17.1. The DR for lakes sampled in 2005 ranged from 1.5 to 55 (Table 17). The average DR in 2005 was 15 with a median of 11.8.

4.2.4 Shoreline Development

Shoreline development ranged from 1.20 to 9.85. Lakes with irregular shorelines and a significant amount of islands had the highest shoreline development. Mean shoreline development in 2004 was 4. Sasaginnigak Lake had the highest shoreline development while Dawson Lake had the least developed shoreline.

4.2.5 Lake Depth

Water depths ranged from less than 1 metre to approximately 25 metres (Table 16). Lakes sampled in 2005 represented a wide range of average depths from 1.8 meters to 14.9 meters (Table 17). Maximum water depth at each lake recorded ranged from 2.2 meters to 20.5 meters.

4.2.6 Water Temperature

Surface water temperature in 2004 ranged from 16.5 to 24.5 °C. Temperatures at one meter depth ranged from 15.5 to 22.6 °C. Temperatures in the bottom water of each lake ranged from near the surface water temperature for shallow lakes to 6 °C for Lake 87 (Brooks Lake) at 15 metres. Temperature profile data indicated that that 27 of the 99 study lakes were thermally stratified at the time of sampling in 2004 (Figures 15 to 18).

4.2.7 Photic Depth

The photic depth ranged from 0.9 to 11.9 meters. In many of the shallow lakes sampled in 2004, the photic depth was greater than the actual depth at the sampling site, indicating a capability for photosynthetic growth throughout the entire water column.

Light extinction profiles in 2004 indicated that the photic depth exceeded the depth of the sample site in 17 out of 99 lakes. Many of these shallow lakes supported extensive submergent macrophyte communities. Wildrice was an abundant and economically important resource in many of these shallow lakes.

Concerning watershed disturbance, lakes with reference watersheds recent and historical watershed harvest had the highest shallowest photic depths followed by lakes with burned watersheds at 3.6 m and 3.10 m respectively i.e. the light extinction coefficient was highest in these lakes (Figure 11). Lakes with watershed harvesting and lakes with both watershed harvesting and watershed fire had very similar fire and harvest showed the next most shallow photic depths at 2.81 and 2.84 m respectively (Figure 10), followed by lakes with watershed fire and "reference" lakes without recently disturbed watersheds.

4.2.8 Secchi Depth

Secchi depth in 2004 ranged from 0.75 m to 4.84 m. Mean Secchi depth was highest in lakes with watershed fire and lowest in lakes with watershed harvesting (Figure 10). However, these differences were not statistically significant ($p>0.05$). Lakes with recent watershed fire, having the highest Secchi depth, are located in the north of the study area and the observed differences may be due to geographic location and different soil and geologic conditions in the northern watersheds. For example there may be less organic soil to provide DOC and fire would burn off the thin soils and reduce any potential DOC input.

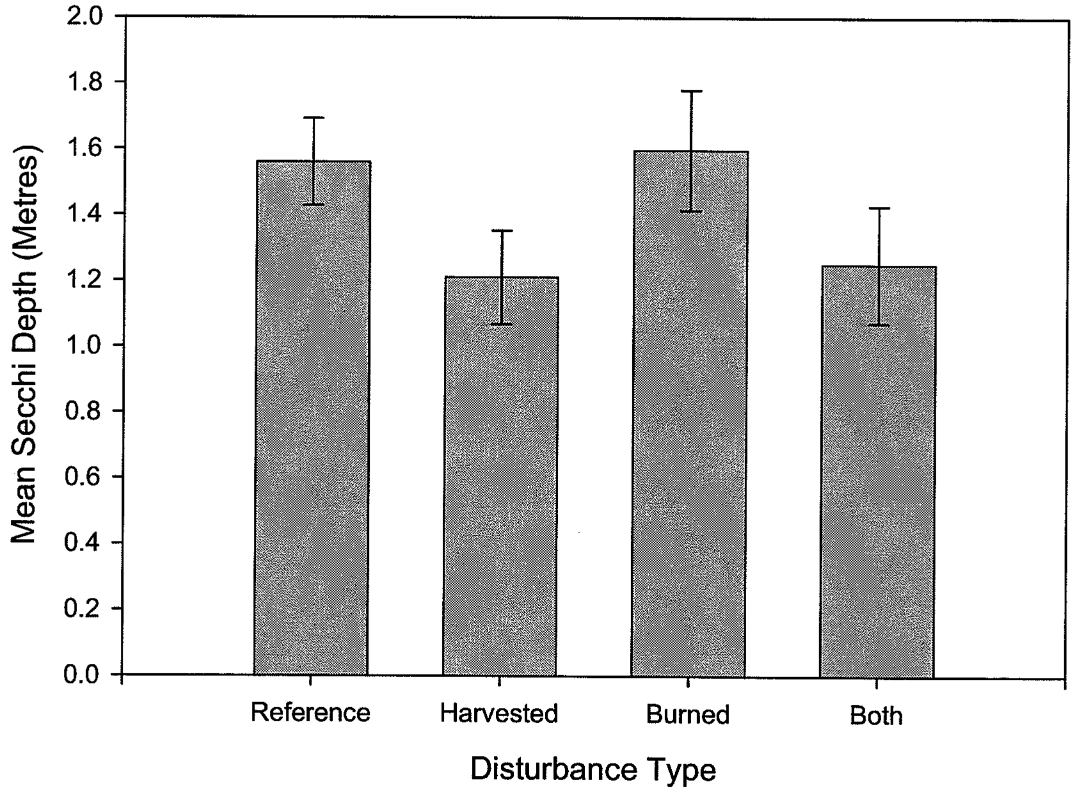

Figure 10: Mean 2004 Secchi depth

+/- Standard error amongst lakes grouped by watershed disturbance type. Reference (n=24), harvested (n=12), (burned n=24), both (n=9). Treatments were not statistically different.

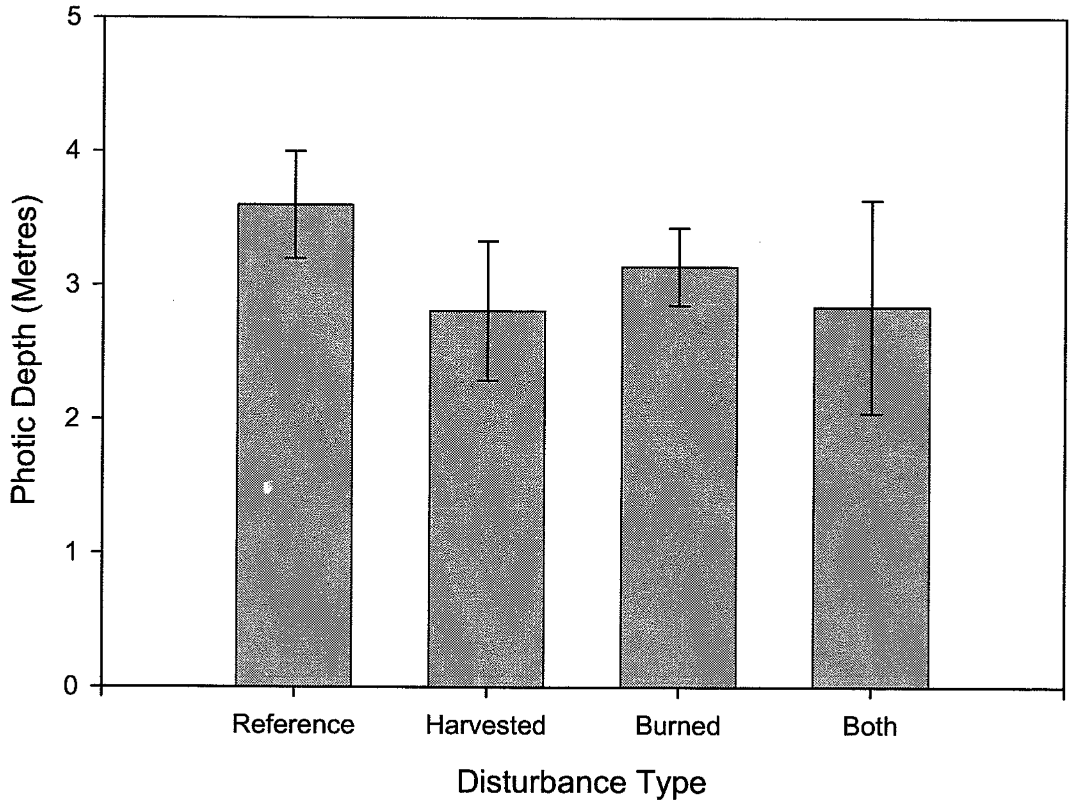

Figure 11: Mean 2004 photic depth

+/- Standard error amongst lakes grouped by watershed disturbance type. Reference (n=24), harvested (n=12), (burned n=24), both (n=9).

4.3 Water Chemistry Results

4.3.1 2004

4.3.2 Oxygen

Dissolved oxygen concentration at the surface ranged from 5.28 to 8.78 mg/L in Lake 42 and Lake 36 (Badou Lake) respectively. Mean dissolved oxygen across the study region was 6.82 mg/L at the surface and 6.46 mg/L at one meter indicating there is a good supply of oxygen to support aquatic life. In lakes that were thermally stratified, dissolved oxygen was occasionally less than 2 mg/L in the hypolimnion (Figures 12 to 15).

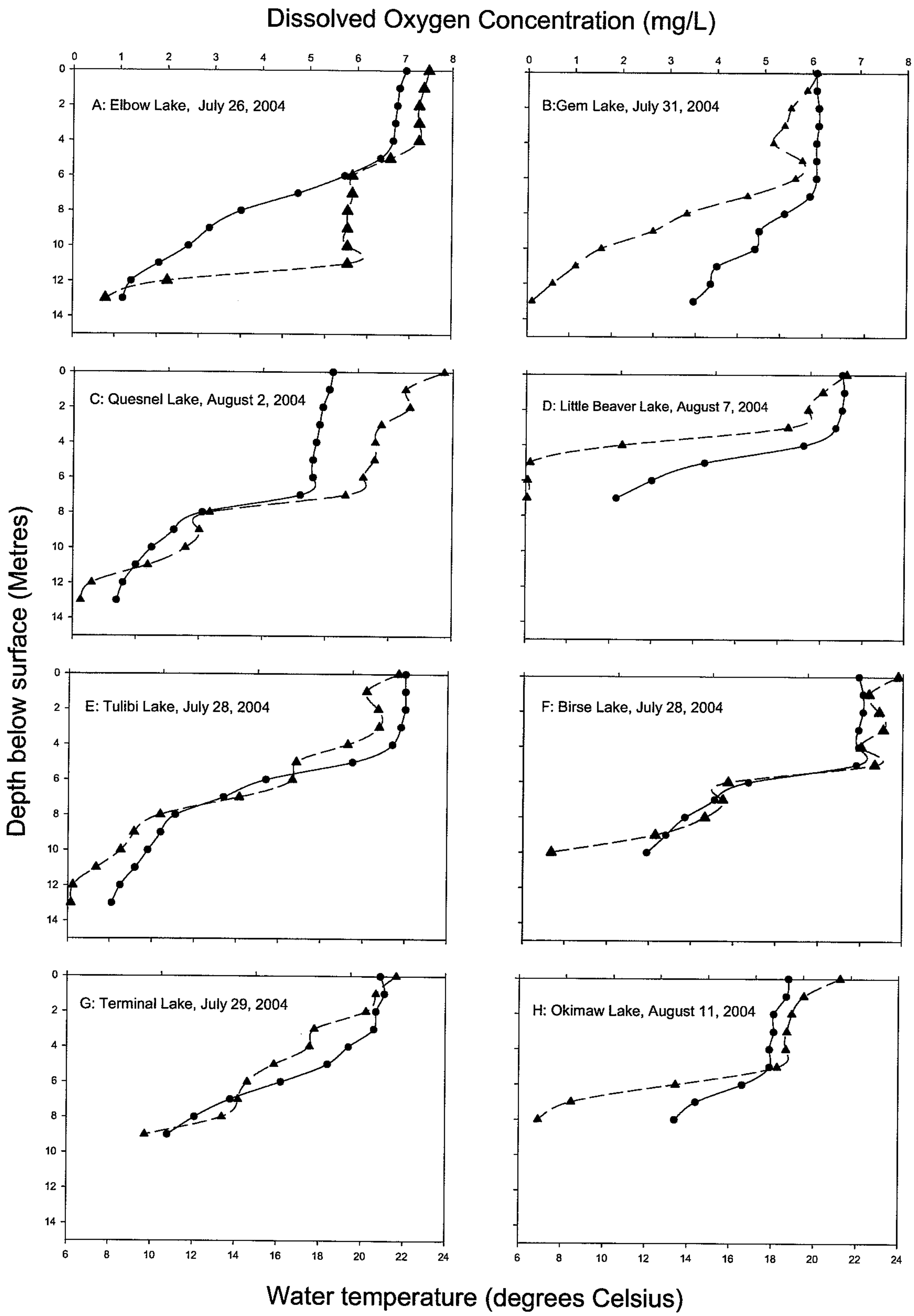

Figure 12: Temperature (solid line) and oxygen (dashed line) profiles for select thermally stratified lakes in 2004

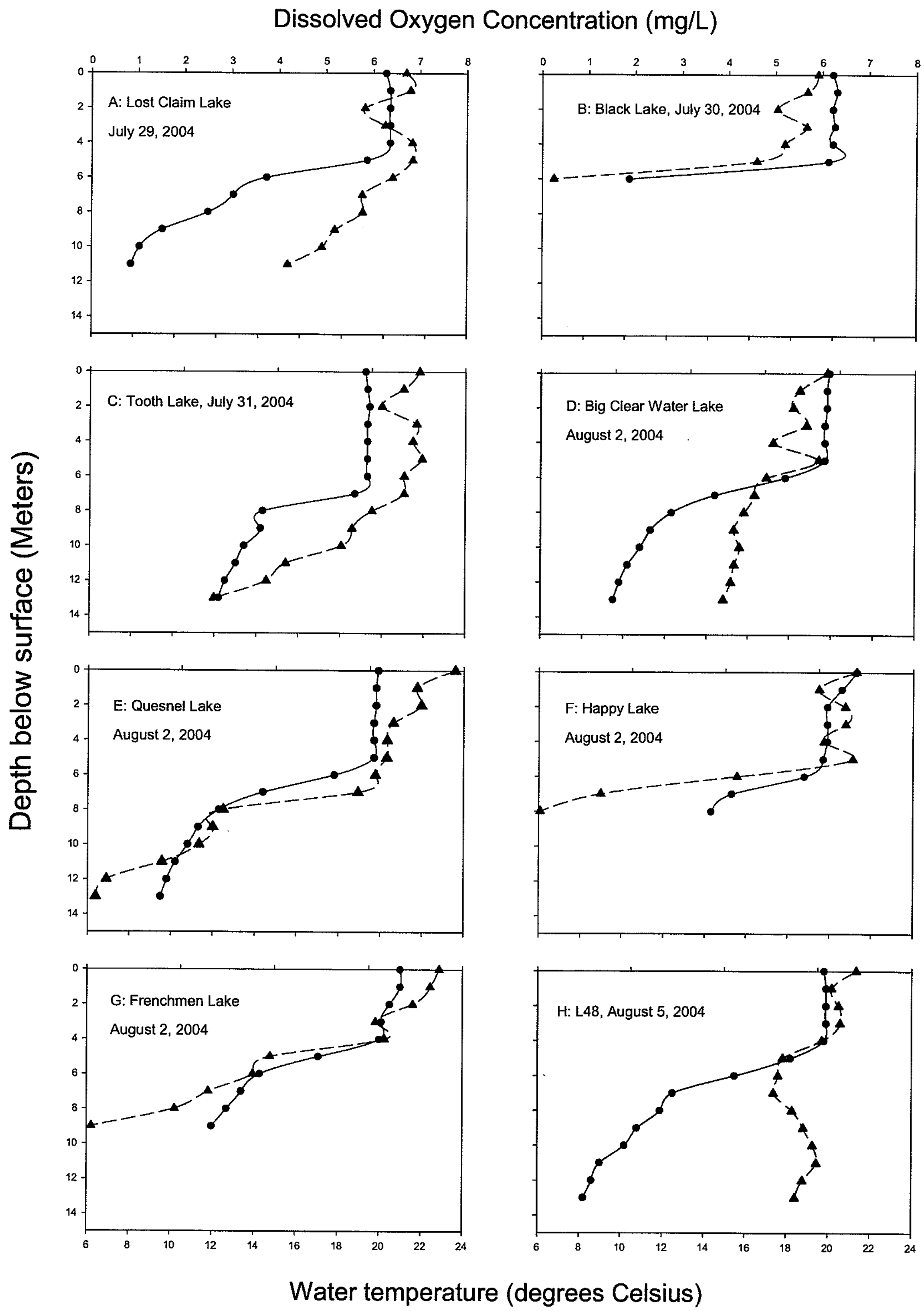

Figure 13: Temperature (solid line) and oxygen (dashed line) profiles for select thermally stratified lakes in 2004

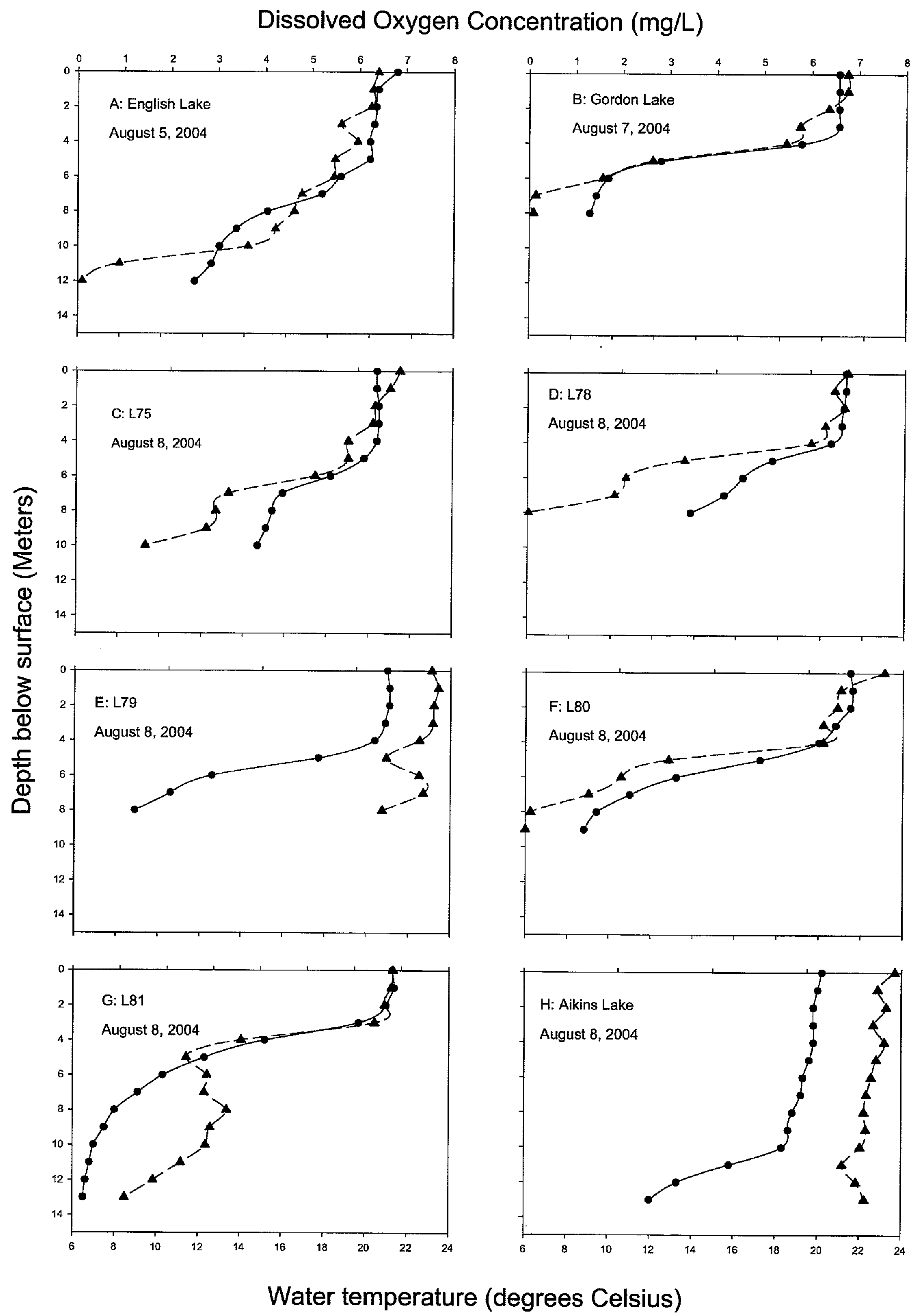

Figure 14: Temperature (solid line) and oxygen (dashed line) profiles for select thermally stratified lakes in 2004

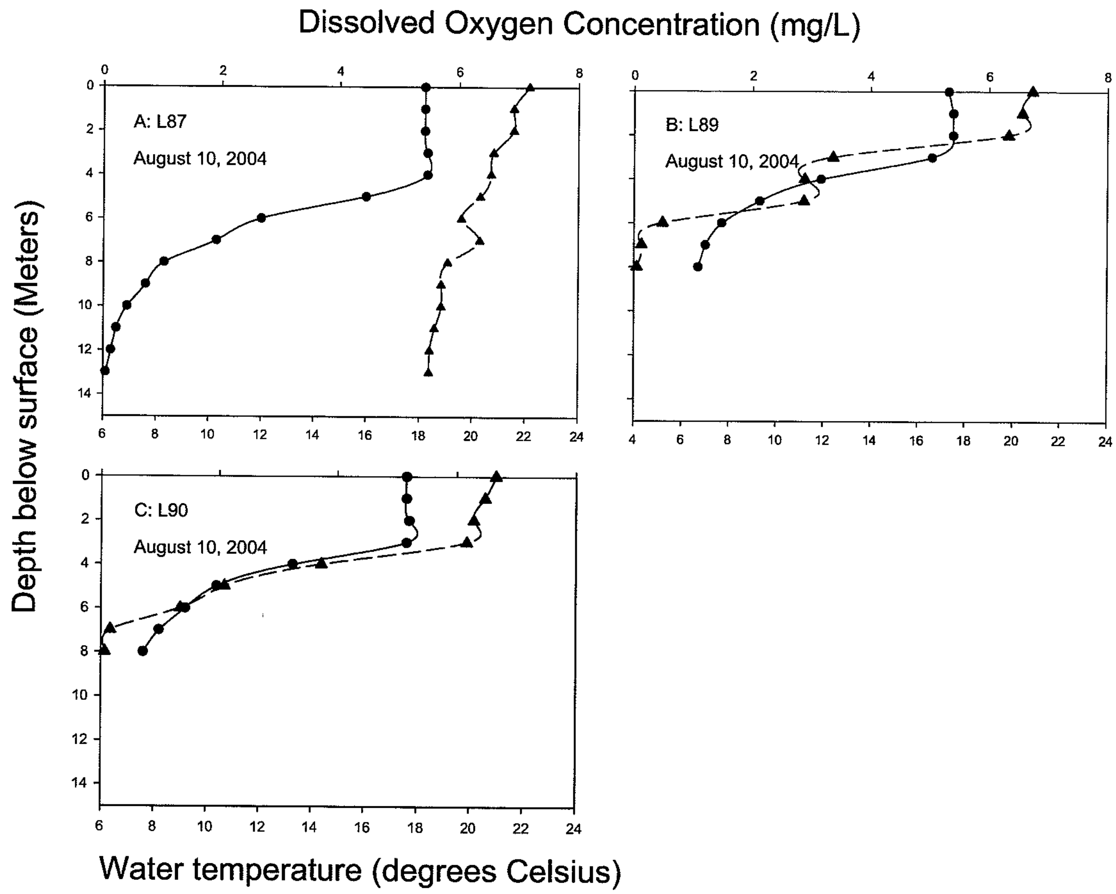

Figure 15: Temperature (solid line) and oxygen (dashed line) profiles for select thermally stratified lakes in 2004

4.3.3 Conductivity

The highest conductivity was measured in Saxton Lake at 177 μS/cm. The lowest conductivity as recorded in L62 at 18 μS/cm. Lakes with watershed harvesting had the highest conductivity (80 μS/cm) whereas reference lakes had the lowest conductivity (mean 31 μS/cm). Lakes with both watershed harvesting and fire had an average conductivity of 43 μS/cm.The average conductivity of the burned lakes was 38 μS/cm.

4.3.4 Major Ions

Calcium measured from the 99 lakes in 2004 ranged from 1.85 to 23.20 mg/L. The mean calcium concentration was 5.3 mg/L. The highest concentrations were measured in Saxton Lake water while the lowest was found in Lake 64. Sodium concentrations ranged from 0.52 to 9.25 mg/L with a mean concentration of 1.1 mg/L. The highest concentration was found in Bernic Lake. Little Beaver Lake had the next highest concentration of 2.74 mg/L. Concentrations of magnesium measured in 2004 ranged from 0.67 to 9.60 mg/L (mean 1.8 mg/L). Similar to calcium the greatest concentrations of magnesium were observed in Saxton Lake. The lowest concentration was found in Lake 62. Potassium concentrations ranged from 0.2 to 3.35 mg/L. The highest concentration was observed in Bernic Lake while the lowest was observed for Gilmour Lake (L70). Sulphate concentration ranged from 0.16 to 6.31 mg/L. Sulphate was highest in Bernic Lake and lowest in Shallow Lake. Mean and median sulphate concentrations were 1.29 and 1.16 mg/L respectively. Of the major ions calcium was the most abundant with a mean concentration of 5.36 mg/l (range 1.85 to 23.20 mg/l).

Magnesium was next abundant with a mean concentration of 1.93 mg/L (range 0.67 to 9.60 mg/l), followed by sodium and potassium with mean concentrations of 1.11 mg/l (range 0.52 to 8.25 mg/l) and 0.72 mg/l (range 0.2 to 3.35 mg/l) respectively.

4.3.5 Total phosphorus and nitrogen

Total phosphorus concentrations for the 99 lakes in 2004 ranged from 5 µg/L to 76 µg/L, with a mean of 18 µg/L (Table 18). Total phosphorus values were highest in Saxton Lake, Farrington Lake and Badou lake at 76, 42 and 39 µg/L respectively. A number of lakes shared low concentrations of total phosphorus in 2004 (less than 10 µg/l). These included Birse Lake, Terminal Lake, Lost Claim Lake, Gordon Lake, Lake 79, Aikins Lake, Lake 89, Lake 90, Peacock Lake, Lake 6, Lake 38, and Bird Lake. The majority of these lakes are reference lakes having less than 30 percent total disturbance within the last 60 years.

Total nitrogen varied throughout the region and generally paralleled trends in total phosphorus (Table 18). Total nitrogen ranged from 392 µg/l to 1478 µg/l. The mean total nitrogen concentration was 721 µg/l. High concentrations of total phosphorus did not always correspond with high nitrogen concentrations ($r=0.77$). For example, Farrington Lake had the second highest concentration of total phosphorus but had the ninth highest nitrogen concentration. Total nitrogen concentration was the highest in Saxton Lake, Badou Lake and Lake 43 at 1478 µg/l, 1179 µg/l and 1130 µg/l respectively.

4.3.6 Nitrogen to Phosphorus Ratio

Ratios of molar concentrations of nitrogen and phosphorus compared to the Redfield ratio of 16 moles nitrogen to one mole phosphorus appeared to indicate that phosphorus is typically more limiting to growth in these lakes. The mean ratio of nitrogen to phosphorus in 2004 was 104 (range 44 for Saxton Lake to 213 for Peacock Lake). The molar ratio of nitrogen to phosphorus above 16 indicated that phosphorus is the limiting nutrient in all of the study lakes (Figure 17)

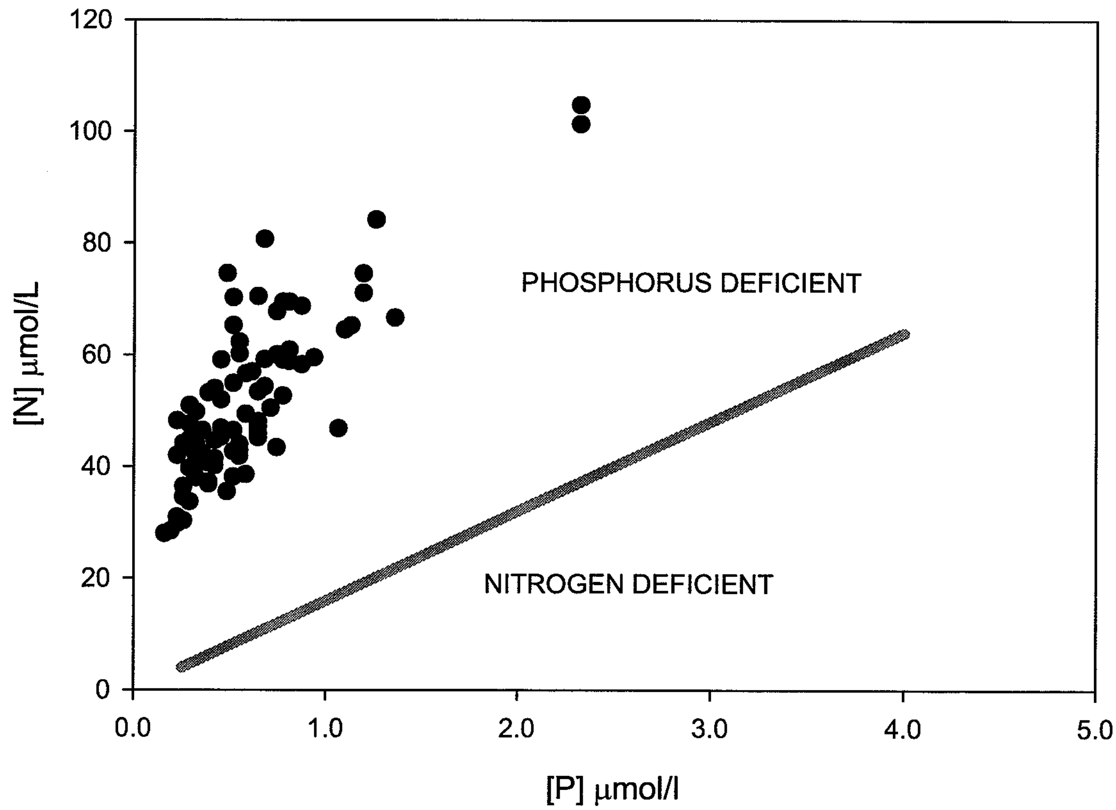

Figure 16: Total nitrogen to phosphorus ratio for 100 Shield lakes in Eastern Manitoba. Bottom line represents molar Redfield Ratio of 16N:1P

4.3.7 Dissolved Organic Carbon:

The average concentration of DOC was 18 mg/L (Table 18). The lowest concentration of DOC was found in Aikins Lake at 7.5 mg/L while Lake 43 had the highest concentration of DOC at 40 mg/L.

4.3.8 Chlorophyll *a*

Chlorophyll *a,* an indicator of phytoplankton biomass, ranged from 2 μg/L to 47 μg/L (Table 18). The highest concentrations were observed in Saxton Lake followed by Badou Lake at 28 μg/L. In many of the lakes, algal blooms were observed to occur. Blooms of phytoplankton were visible from both the air and water. From the air these blooms appeared as large green streaks across the lake parallel to the wind direction. From visual examination of lake water, the predominant phytoplankton genera in lakes with blooms appeared to be *Aphanizomenon.* Phytoplankton blooms were observed to occur in 2004 in L36 (Badou Lake), L47 (Wanipigow Lake), L49, L51 (English Lake), L52 (Dawson Lake), L53 (Boulette Lake), L61 (Dogskin), L83. In 2005, phytoplankton blooms were observed in L60 and L100 (Saxton Lake). Blooms in many cases were observed in remote lakes with no indication of human or natural watershed disturbance (e.g L60, L61).

Plate 6: Bloom of phytoplankton in Walton Lake (located 6km South West of Bissett) (N50.9828 W95.7281) observed from the air in September 2004. Note: Walton Lake was not one of the study lakes. Photo credit Brian Kotak.

Total chlorophyll combined with total phosphorus is an indicator of the trophic or nutrient status of a lake. Water quality results from 2004 indicate that 79 percent of the lakes can be categorised as oligotrophic to mesotrophic; of these five percent of the lakes were oligotrophic (Figure 19). A number of the lakes can be classified as eutrophic (21 percent). It is interesting to note that of the eutrophic lakes, 39 percent of their watersheds have experienced forest fire between 1980 and 2002 and 56 percent of the eutrophic lakes have experienced watershed harvesting between 1968 and 2004. Of the eutrophic lakes only two (L43 and L8) were subject to forest harvesting within the last five years (Table 14).

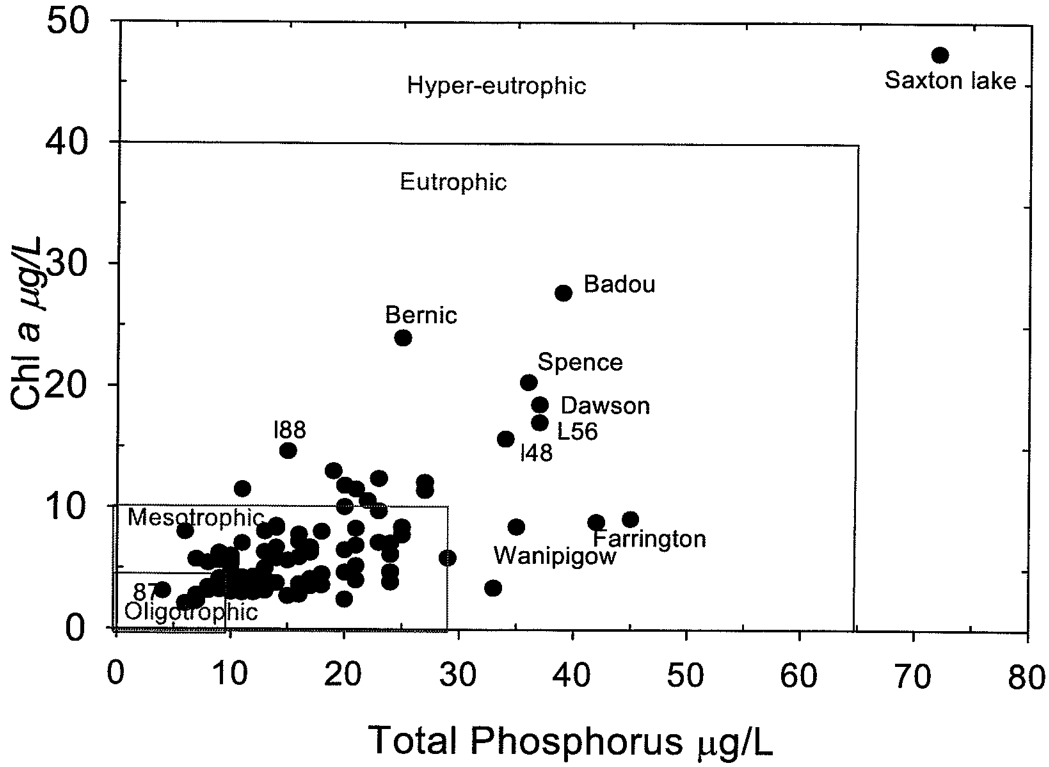

Figure 17: Trophic status of study lakes in 2004.

Of the eutrophic lakes, the majority of watersheds were historically subjected to watershed fire, watershed harvesting or both Note: trophic state criteria from Carlson (1977)

Table 18: Summary of 2004 water quality data for 99 boreal forest lakes in eastern Manitoba

Parameter	Units	Min	Mean	Median	Max
Secchi depth	m	0.42	1.56	1.40	4.84
Photic depth	m	0.85	3.68	3.02	11.93
Conductivity	µS/cm	18.00	44.43	34.00	175.00
pH		6.28	7.43	7.41	8.37
Alkalinity	µeq calcium /L	80	325	228	1740
Nitrate/ Nitrite	µg/L	<1	4.89	2.00	75.00
SUSP N	µg/L	57	153	129	674
TDN	µg/L	300	567	523	950
TN	µg/L	392	720	662	1419
SUSPP	µg/L	4	12	9	65
TDP	µg/L	<1	6	5	21
TP	µg/L	5	18	16	72
DIC	mg/L	0.60	3.46	2.43	20.43
DOC	mg/L	7.56	18.52	17.07	39.60
SUSP C	mg/L	6.60	14.71	11.94	67.45
CHLA	µg/L	2.09	7.24	5.80	47.48
SRSI	mg/L	0.04	0.81	0.67	2.36
Chloride	mg/L	0.06	0.39	0.28	2.68
Sulphate	mg/L	0.16	1.34	1.16	6.50
Sodium	mg/L	0.52	1.12	0.99	9.25
Potassium	mg/L	0.20	0.72	0.66	3.35
Magnesium	mg/L	0.67	1.88	1.46	9.50
Calcium	mg/L	1.85	5.24	3.76	23.20

4.3.9 2004 Hypolimnion Samples

Water chemistry from the 8 hypolimnion samples collected in 2004 was similar to surface water samples with a few exceptions (Table 19). Chloride, sulphate, potassium, pH, calcium and alkalinity were not appreciably different between surface water and hypolimnion samples. Soluble reactive silica was always higher in the hypolimnion as opposed to the epilimnion. Nitrate concentrations were significantly elevated in hypolimnion samples whereas in many of the surface water samples concentration of nitrate was below the detection limit of 1 μg/L. Suspended nitrogen was significantly higher in surface water samples than hypolimnion samples. Conversely dissolved nitrogen was highest in the hypolimnion samples. Total phosphorus concentrations were similar between epilimnion and hypolimnion samples. However, the hypolimnion of Lake 81 had significantly elevated concentrations of dissolved phosphorus. Dissolved organic carbon was always highest in the epilimnion samples. Not surprisingly, chlorophyll *a* was also elevated in the epilimnion samples compared to hypolimnion samples with the exception of Gordon Lake (L69), which had a higher chlorophyll *a* concentration in the hypolimnion sample versus the epilimnion sample.

Table 19: Comparison of water chemistry in surface and hypolimnion samples collected from 8 Manitoba boreal shield lakes in Mid-summer 2004

LAKE ID	Location	NO_3	SUSPN	TDN	TN	SUSP P	TDP	TP	DOC	CHL *a*	SRSI	CL	SO_4	Cond	Na	K	Ca	pH	Alk
		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µmol/L	µg/L	mg/L	mg/L	mg/L	$\mu S/Cm^2$	mg/L	mg/L	mg/L		µeq/l
48	Surface	4	86	670	756	6	7	13	2120	5.01	0.996	0.19	1.08	36	1.07	0.50	4.21	7.36	237
	Hypolimnion	131	61	710	771	4	10	14	1895	1.62	1.590	0.25	1.25	37	1.09	0.58	4.04	7.27	236
69	Surface	1	156	510	666	7	2	9	935	3.25	0.214	0.35	1.42	32	1.00	0.49	3.31	7.55	221
	Hypolimnion	62	129	610	739	8	3	11	865	4.00	0.435	0.38	1.37	33	0.98	0.51	3.60	7.56	216
75	Surface	3	85	435	520	8	4	12	1315	3.88	0.934	0.28	1.08	25	0.90	0.52	2.77	7.19	140
	Hypolimnion	34	57	475	532	7	7	14	1215	1.77	1.300	0.28	1.16	26	0.91	0.53	2.79	7.22	138
77	Surface	1	114	420	534	10	6	16	1100	7.78	0.293	0.26	1.13	29	0.99	0.56	3.13	7.42	183
	Hypolimnion	8	68	440	508	10	7	17	1085	3.26	0.424	0.26	1.01	29	0.98	0.56	3.23	7.43	180
79	Surface	<1	98	300	398	4	2	6	710	2.09	0.222	0.16	1.11	42	1.21	0.69	4.86	7.81	352
	Hypolimnion	53	39	295	334	4	2	6	565	1.12	0.546	0.18	1.15	43	1.19	0.71	4.94	7.79	347
81	Surface	<1	111	525	636	8	5	13	1395	6.34	0.730	0.08	1.09	36	1.22	0.56	3.96	7.54	258
	Hypolimnion	175	64	620	684	14	22	36	1330	1.20	1.760	0.12	1.29	38	1.19	0.64	4.08	7.52	257
84	Surface	<1	109	315	424	8	<1	8	630	2.79	0.270	0.42	1.81	34	0.93	0.53	3.70	7.54	228
	Hypolimnion	78	22	335	357	3	<1	3	555	0.69	0.652	0.46	1.87	35	0.94	0.54	3.66	7.55	235
87	Surface	1	87	305	392	5	<1	5	810	3.13	0.739	0.19	1.53	23	0.83	0.48	2.32	7.12	134
	Hypolimnion	99	51	355	406	5	<1	5	645	1.16	1.160	0.32	1.71	24	0.87	0.51	2.44	7.21	134

4.4.0 Relationship between geographic location and water quality among study lakes

Due to the large study area and possible geographic influence on water quality, the relationship between lake water quality and geographic location of each lake was examined. Latitude did not correspond strongly with any of the water quality variables (Table 21). Longitude strongly correlated with the proportion of wetlands in a watershed (r=0.50). As watersheds became closer to Lake Winnipeg the proportion of wetlands in each watershed were observed to increase. Longitude was representative of changing soil conditions in the watershed and was strongly associated with concentrations of total dissolved nitrogen (r=.57), total nitrogen (r=.46), total dissolved phosphorus (r=.59) and dissolved organic carbon (r = .49). As longitude increased (Lakes became more westerly in location), the concentrations of these parameters were observed to increase.

Table 20: Pearson product moment correlation coefficients and P values between water quality variables and geographic location of 73 Boreal Shield Lakes (note lakes with watersheds originating in Ontario were excluded from the analysis)

	Latitude	*P* value	**Longitude**	*P* value
Latitude	-	-	0.24	**
Longitude	0.24	**	-	-
Proportion of wetlands	0.08	NS	0.50	***
Depth at sample site	0.31	NS	0.05	NS
Secchi Depth	-0.12	NS	-0.12	NS
Photic Depth	0.16	NS	-0.17	NS
Nitrate	-0.06	NS	0.24	**
Suspended Nitrogen	0.07	NS	0.08	NS
Total Dissolved Nitrogen	-0.04	NS	0.60	***
Total Nitrogen	0.00	NS	0.49	***
Suspended Phosphorus	0.11	NS	0.24	**
Total Dissolved Phosphorus	0.23	*	0.59	***
Total Phosphorus	0.18	NS	0.42	***
Dissolved Organic Carbon	-0.11	NS	0.50	***
Chlorophyll *a*	-0.05	NS	0.22	*
Chloride	-0.09	NS	0.09	NS
Sulphate	-0.33	***	-0.38	***
Conductivity	-0.08	NS	0.12	NS
pH	0.03	NS	0.16	NS
Alkalinity	-0.02	NS	0.13	NS
Sodium	-0.12	NS	0.07	NS
Potassium	-0.21	NS	0.04	NS
Magnesium	0.00	NS	0.31	***
Calcium	-0.05	NS	0.10	NS

P values: NS=not statistically significant ($P>0.10$), *=$P<0.10$, ** $P<0.05$, *** $P<.01$

4.4 Water Quality In 2005

Secchi depth in 2005 ranged from 0.28 to 2.58 metres (Table 22). Mean Secchi depth in 2005 was 1.33 meters. L64 in May had a Secchi depth greater than the water column depth of 1.8 meters. The lowest Secchi depth was measured in shallow L43 on an extremely windy day. It is likely the wind and wave action causing re-suspension of sediment was responsible for this low Secchi disk reading. Mean Secchi depth was highest in the spring (1.44 m), and lowest in August (1.11 m). Average September Secchi depth was (1.18 m) (Table 22).

Surface water temperature in May ranged from 13.1 to 20.9 ˚C. Mean May water temperature was 16.0 ˚C. Mean surface water temperature in August was 22.0 ˚C (range 20.2 to 23.3 ˚C). In September, the mean surface water temperature was 15.5 ˚C (range 15.2 to 17.8 ˚C).

Conductivity measured ranged from 15 µs/cm in Lake 64 to 173 $\mu s/cm^2$ for Saxton Lake respectively. Mean conductivity in 2005 was 37 $\mu S/cm^2$. Average conductivity was highest in May (37.7 $\mu s/cm^2$) and September (36.2 µS/cm) and lowest in August (35.4 µS/cm) (Table 22).

In 2005, pH ranged from 5.8 to 8.74. Median pH was 6.78. May samples from Kinsley, Owl and Brooks Lake all had spring pH values in the high end of the range. Kakaki Lake had the most acidic lake water in May (pH= 5.9), August (pH= 5.8) and September (pH=6.0). Median pH was highest in May (pH= 7.1) and lower in August (pH= 6.75) and September (pH= 6.71) (Table 22).

Dissolved organic carbon concentration ranged from 7 to 49 mg/L for Glen Lake in May and Lake 43 in September. Seasonal average concentrations were 16.2 mg/L, 23.5 mg/L and 25.2 mg/L for May, August and September respectively.

4.5 Nitrogen and Phosphorus

Concentrations of total phosphorus observed in 2005 ranged from 8 to 157 µg/L. As in 2004, the highest concentrations were observed in August in Saxton Lake. The lowest concentration was measured for Lake 86 (Brooks Lake) in August samples. Mean total phosphorus was 27 µg/L. Mean concentration of total phosphorus was 22 µg/L in May and 34 µg/L in August and September respectively (Table 22).

Nitrate concentrations ranged from below the detection limit of 10 µg/L to 240 µg/L. The highest concentrations were observed in May samples of Lake 68. Lake 68 was later removed from the sampling regime because it was too short for the aircraft used in subsequent sampling. Lake 43 had the next highest concentration of nitrate at 180 µg/L in September.

Total Kjeldahl Nitrogen in 2005 ranged from 90 µg/L (Springer Lake) to 2500 µg/L (Saxton Lake) (Table 22). The average TKN concentration in 2005 was 760 µg/L. Mean TKN concentrations for May, August and September were 750 µg/L, 970 µg/L and 650 µg/L respectively.

Table 21: Summary of 2005 water quality data for 21 Eastern Manitoba boreal forest lakes sampled inclusively in May, August and September 2005

		TDP µg/L	TP µg/L	TKN µg/L	Nitrate µg/L	TN µg/L	SO_4^{-2} mg/L	Ca^{+2} mg/L	K^+ mg/L	Mg^{+2} mg/L	Na^+ mg/L	Conductivity µS/cm	Alk µg/L	pH	Chl a µg/L	DOC mg/L
May	min	4	12	433	<10	500	9.0	1.4	0.4	0.5	0.5	16.1	5.7	5.9	2.9	7.0
	mean	13	22	748	64	809	15.7	3.9	0.8	1.6	1.0	37.8	15.6		6.5	16.2
	median	9	21	633	67	730	15.0	3.0	0.8	1.2	1.0	30.4	12.0	7.1	6.0	15.0
	max	40	36	2533	180	2543	24.0	17.2	1.4	7.9	1.6	159.7	78.7	8.7	13.0	27.0
August	min	5	14	600	<10	600	12.0	1.6	0.4	0.6	0.5	15.3	5.0	5.8	6.0	10.2
	mean	17	34	965	33	982	25.7	4.8	0.9	1.8	1.0	35.4	14.2		29.1	23.5
	median	9	23	900	20	900	22.0	3.4	0.8	1.2	0.9	26.2	9.0	6.8	24.8	21.3
	max	84	157	1600	80	1680	43.0	21.4	1.8	9.6	1.8	160.0	78.0	7.8	155.0	40.4
September	min	5	17	90	<10	90	20.0	1.7	0.4	0.6	0.5	15.1	5.0	6.0	3.0	10.0
	mean	18	34	650	58	682	44.6	5.0	0.8	1.8	0.9	36.2	15.0		22.4	25.3
	median	11	28	700	45	700	37.0	3.5	0.8	1.3	0.9	26.4	9.5	6.7	19.8	20.7
	max	60	87	1200	180	1380	110.0	21.0	1.6	9.1	1.8	173.0	84.0	7.7	46.7	49.0

4.7 Nitrogen to Phosphorus Ratio

Between August and September, a significant shift in nitrogen to phosphorus ratios was observed ($p<.001$). All ratios with the exception of Springer Lake were above the theoretical Redfield molar nitrogen to phosphorus ratio of 16 moles nitrogen to one mole phosphorus (Figure 20). In 19 of 21 lakes, the N:P ratio decreased between 11 to 90 percent from May to September. Dramatic changes in the N:P ratio through the summer were observed in Saxton lake which decreased from 155 in May to 23 and 21 in August and September. The N:P ratio in Springer Lake decreased from 130 in August to 7 in September. In Lake 43 the N:P ratio increased through the summer from 85 in May to 105 in September.

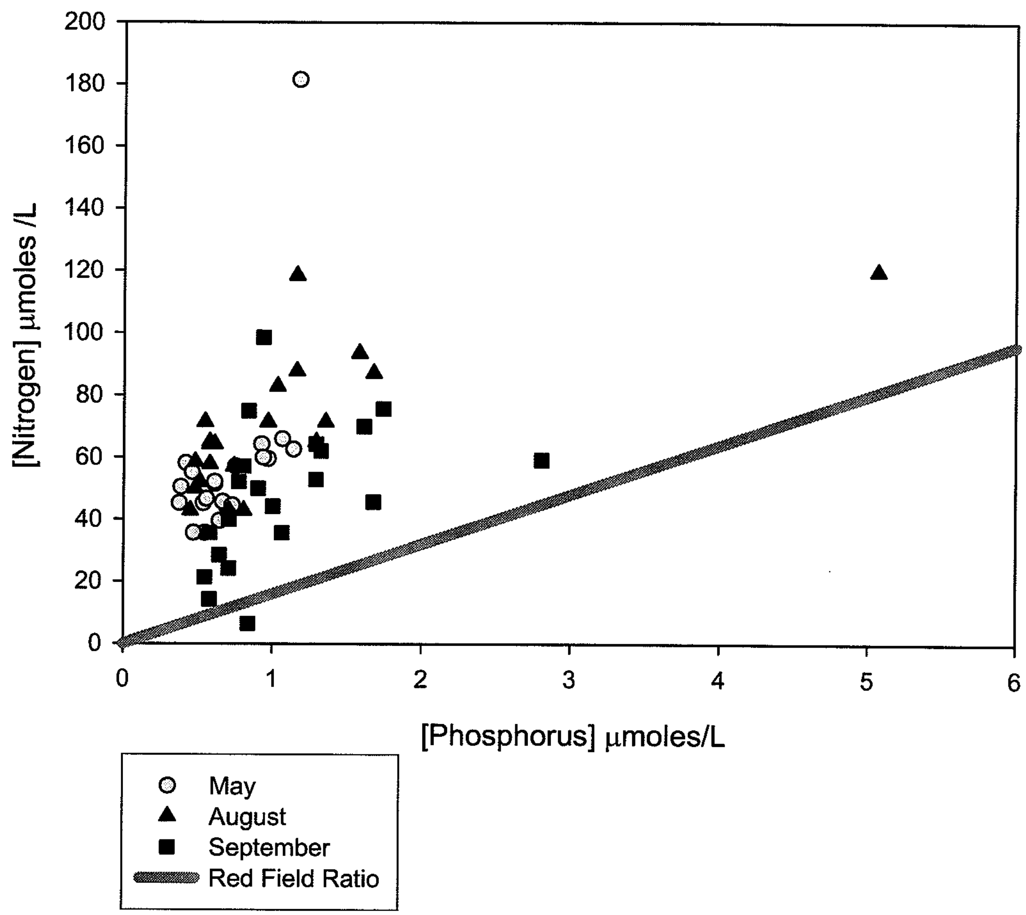

Figure 18: Seasonal 2005 nitrogen to phosphorus ratios

21 Shield lakes in Eastern Manitoba sampled in May (Circles), August (Triangles), and September (Squares). Bottom line represents molar Redfield Ratio of 16N:1P

4.6.10 Major Ions

Congruent to 2004, calcium was the most abundant ion in 2005 with a mean concentration of 3.9 mg/L followed by magnesium (1.6 mg/L), sodium (1.0 mg/L) and potassium (0.8 mg/L) (Table 21). Calcium ranged from 1.4 to 21 mg/L (Mean = 3.9 mg/L). Saxton Lake again had the highest calcium concentration, remote L64 had the lowest calcium concentration. Magnesium concentrations ranged from 0.50 to 9.55 mg/L for L64 to Saxton Lake. Potassium ranged from 0.33 to 1.79 mg/L (mean = 0.78 mg/L). The highest concentration was measured in Lake 43 in September while the lowest concentrations were observed in Lake 63 in August. Sulphate ranged from 9mg/L to 110 mg/L in September samples of Happy Lake and Saxton Lake respectively. Mean sulphate concentration was 28 mg/L.

Alkalinity was significantly higher in Saxton Lake than any of the other lakes sampled in 2005 at between 78 – 84 mg/L as ($CaCO_3$). Alkalinity was generally low in the study lakes with a mean concentration of 13 mg/L. Alkalinity was lowest in Kakaki Lake in May at 5 mg/L. Mean concentration of alkalinity was highest in the spring (15.6 mg/L), and lowest in August (14.2 mg/L). The mean September concentration of alkalinity was 15.0 mg/L.

4.6.11 Chlorophyll *a*

Average chlorophyll concentrations for May, August and September were 6.4, 27.6 and 22.4 μg/L respectively (Table 21). Chlorophyll *a* concentration was highest in Happy Lake in May, Saxton Lake in August, and Round Lake in September at 17, 155 and 46 μg/L respectively. Kakaki and Okimaw Lakes had the lowest concentration of chlorophyll in May and August at 2 and 6 μg/L respectively. Kakaki Lake had the lowest chlorophyll concentration again in September at 3 μg/L.

4.6.12 Microcystin

Microcystin was detected in 15 out of 28 lakes in May, two lakes in August and three lakes in September 2005 (Table 22). Total microcystin concentrations were low. The average concentration detected was 0.20 μg/L. In May, microcystin concentrations was also variable within each lake. For example, only one out of three sites on Boulette, Glen, Kinsley, Okimaw, Round, Spence, Terminal, and L63 had detectable concentrations of microcystin. Microcystin concentrations were also variable through the season in lakes that had detectable concentrations. Happy Lake had detectable concentrations of microcystin in September but not in August or May. Likewise, L59 had microcystin only in August samples. Eastland Lake samples had detectable microcystin in August and May but not September. There was no clear relationship between detected concentrations of microcystin between either chlorophyll a concentration or nitrogen to phosphorus ratio (Figure: 21 and 22).

Table 22: 2005 microcystin results.

Note sampling occurred at three locations in each lake in May and a central location in August and September. Dashed line indicates lake could not be sampled because it was too small for the aircraft used

		May Result (ug/L MCLR-equivalent)			August	September
Lake ID	Lake name	Site A	Site B	Site C	Central Site	
7	Metcalfe	<0.10	<0.10	<0.10	-	-
8	Kinsley	<0.10	0.10	<0.10	<0.10	<0.10
16	Eastland	<0.10	0.11	0.13	0.14	<0.10
18	Glen	<0.10	<0.10	0.39	<0.10	<0.10
19	Terminal	<0.10	0.17	ND	<0.10	<0.10
43	un-named	<0.10	<0.10	<0.10	<0.10	0.10
44	Happy	<0.10	<0.10	<0.10	<0.10	0.12
44	Springer	0.23	0.15	<0.10	<0.10	<0.10
45	Spence	<0.10	<0.10	0.14	<0.10	<0.10
52	Boulette	0.10	<0.10	<0.10	<0.10	<0.10
57	Owl	<0.10	<0.10	<0.10	<0.10	<0.10
58	Farrington	0.18	0.11	0.17	<0.10	<0.10
59	un-named	<0.10	<0.10	<0.10	0.48	<0.10
60	un-named	<0.10	<0.10	<0.10	<0.10	0.70
63	un-named	<0.10	<0.10	0.13	<0.10	ND
64	un-named	<0.10	<0.10	<0.10	<0.10	<0.10
65	Manning	<0.10	<0.10	<0.10	-	-
67	un-named	<0.10	<0.10	<0.10	<0.10	-
68	un-named	<0.10	<0.10	ND	-	-
76	Round	0.10	<0.10	<0.10	<0.10	<0.10
80	un-named	<0.10	<0.10	<0.10	<0.10	<0.10
87	Brooks	0.85	0.17	0.11	<0.10	-
92	West Rat	0.13	0.14	ND	-	-
94	Rainy	0.11	0.14	-	-	-
97	un-named	<0.10	<0.10	<0.10	<0.10	<0.10
98	Kakaki	<0.10	0.24	0.24	<0.10	<0.10
99	Okimaw	0.10	<0.10	<0.10	<0.10	<0.10
100	Saxton	<0.10	<0.10	<0.10	<0.10	<0.10
	min	<0.10	<0.10	<0.10	<0.10	<0.10
	median	0.12	<10	<10	<10	<10
	mean*	0.23	0.15	0.19	0.31	0.31
	max	0.85	0.24	0.39	0.48	0.70

* mean concentration detected when above the limit of detection

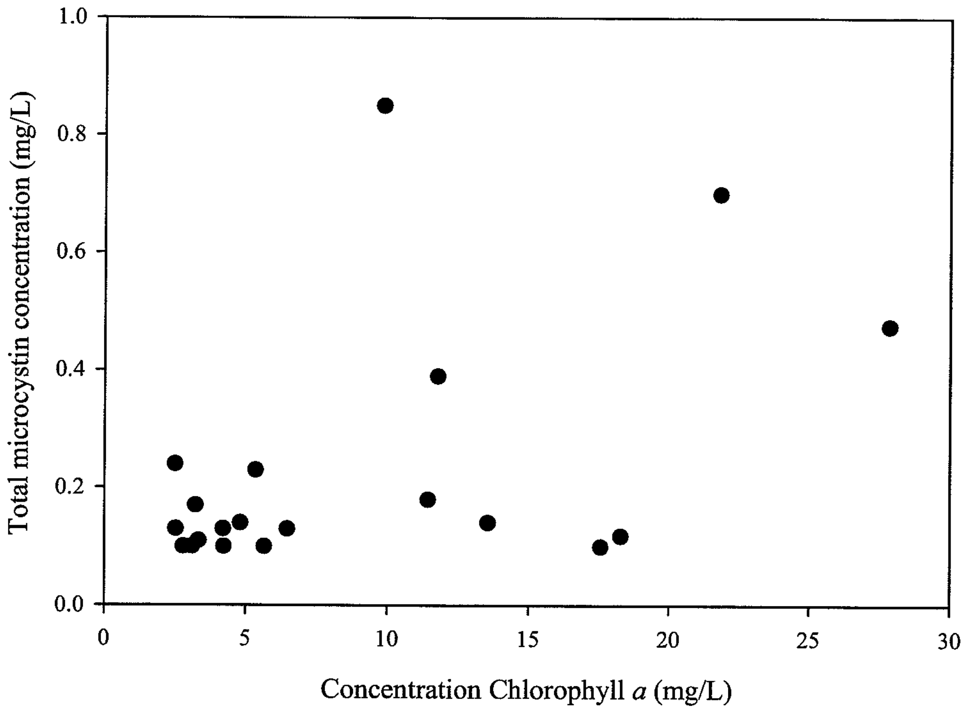

Figure 19: Microcystin concentration in lake water versus chlorophyll *a* concentration

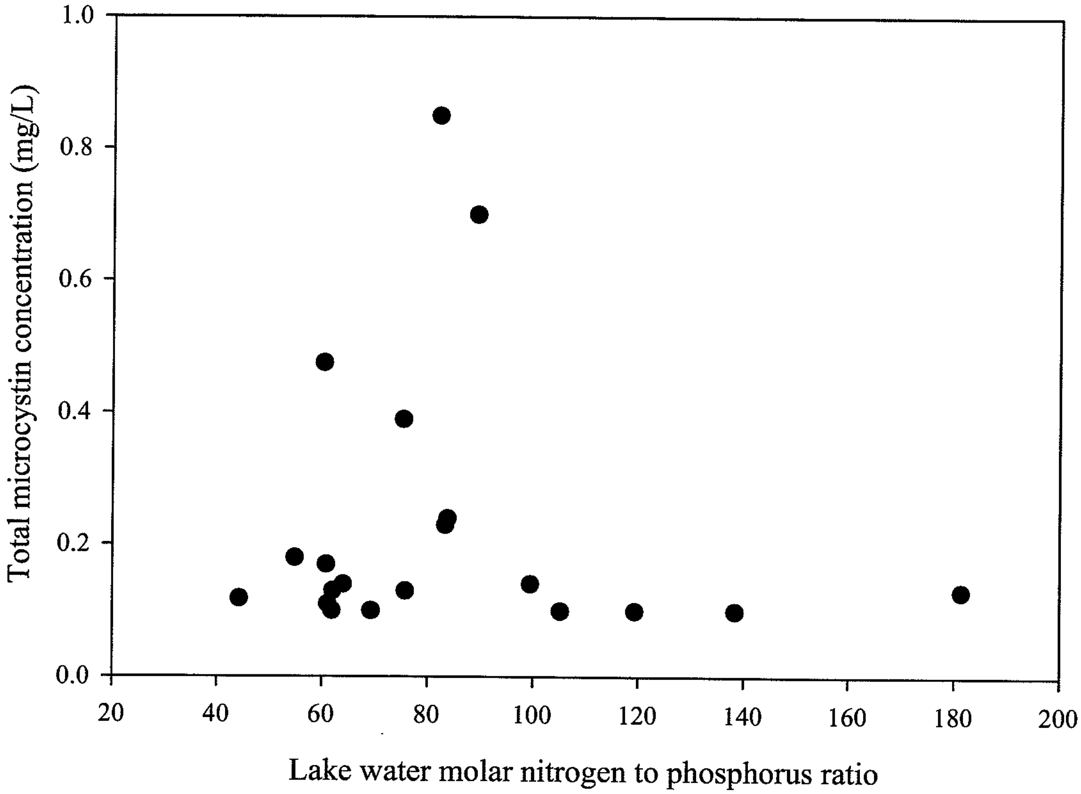

Figure 20: Microcystin concentration versus the N:P ratio

4.6.13 Spatial Variation within Each Lake

May 2005 samples, which were taken at three locations within each lake, indicate that the central sampling site of 2004 was representative of the overall water quality. Only site C on Lake 92 had total phosphorus and nitrogen concentrations that were substantially different from sites A or B. Site C was considerably more shallow at 1.3m versus >2 m for A or B. The higher observed nutrient concentrations may be indicative of the shallow nature of this site and potential for re-suspended sediment from wave action entering the water samples. With respect to chlorophyll concentrations, intra lake samples were generally similar to one another in concentration. The one exception was Happy Lake. While Happy Lake Site A had a concentration of 17 µg/L, Sites B and C had concentrations of 10 and 8 µg/L respectively.

4.6.14 Seasonal Comparison 2005

Concerning seasonal variation within each lake, several trends can be observed. Average total phosphorus increased in concentration through the open water season (Figure 23). Total nitrogen concentration was the highest in August and May samples and decreased substantially on average in September samples (Figure 24). Total dissolved solids and sulphate increased substantially on average through the open water season whereas only slight increases in hardness and calcium occurred (Figures 25 and 26). Alkalinity decreased in August from May concentrations and increased to near May concentrations in September. Changes observed in TP from May to September were significant at ($p<.01$). Total nitrogen increased significantly from May to August however, the overall total nitrogen concentration in September was not significantly different from May samples. Chlorophyll *a* concentrations were markedly different between May, August and September samples. While average chlorophyll *a* was 6 μg/L in May samples, it was 28 μg/L in August and 22 μg/L in September. The August mean was highly affected by Saxton Lake which had a very high chlorophyll *a* concentration of 155 μg/L (Table 21). Median chlorophyll concentrations were very similar between August and September at 20.3 and 19.8 μg/L respectively. Dissolved organic carbon concentration increased substantially through the open water season ($p<0.01$). The most dramatic increase in DOC occurred from May to August 2005 (Figure 27).

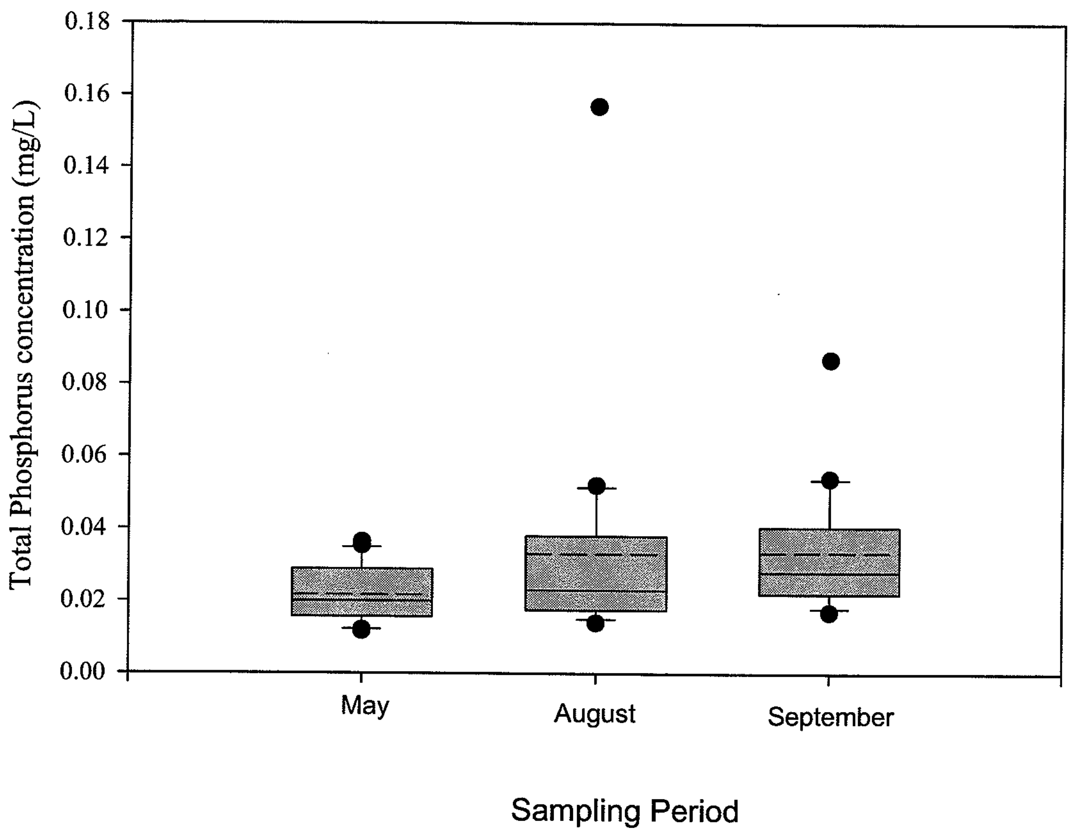

Figure 21: Seasonal 2005 total phosphorus concentrations

Box plots represent median total phosphorus concentration (solid line), mean (dashed line) 10th and 25th 70th and 90th percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers.

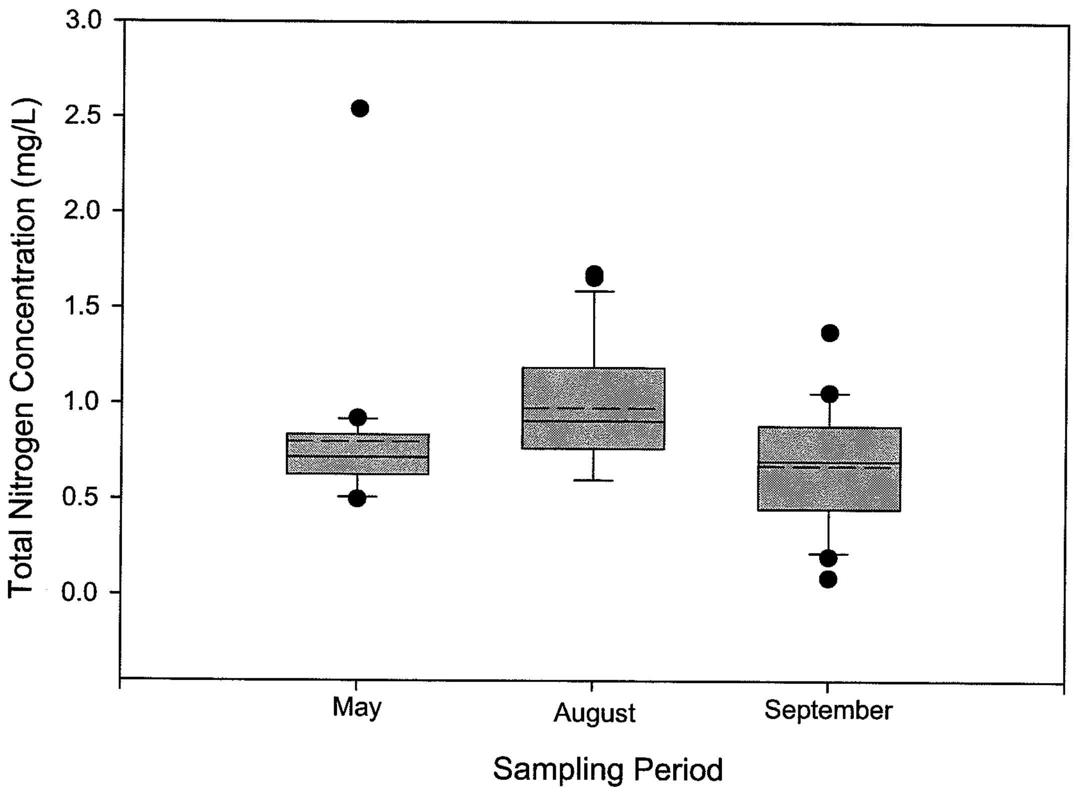

Figure 22: Seasonal 2005 total nitrogen concentrations

Box plots represent median total nitrogen concentration (solid line), mean (dashed line) 10^{th} and 25^{th} 70^{th} and 90^{th} percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers.

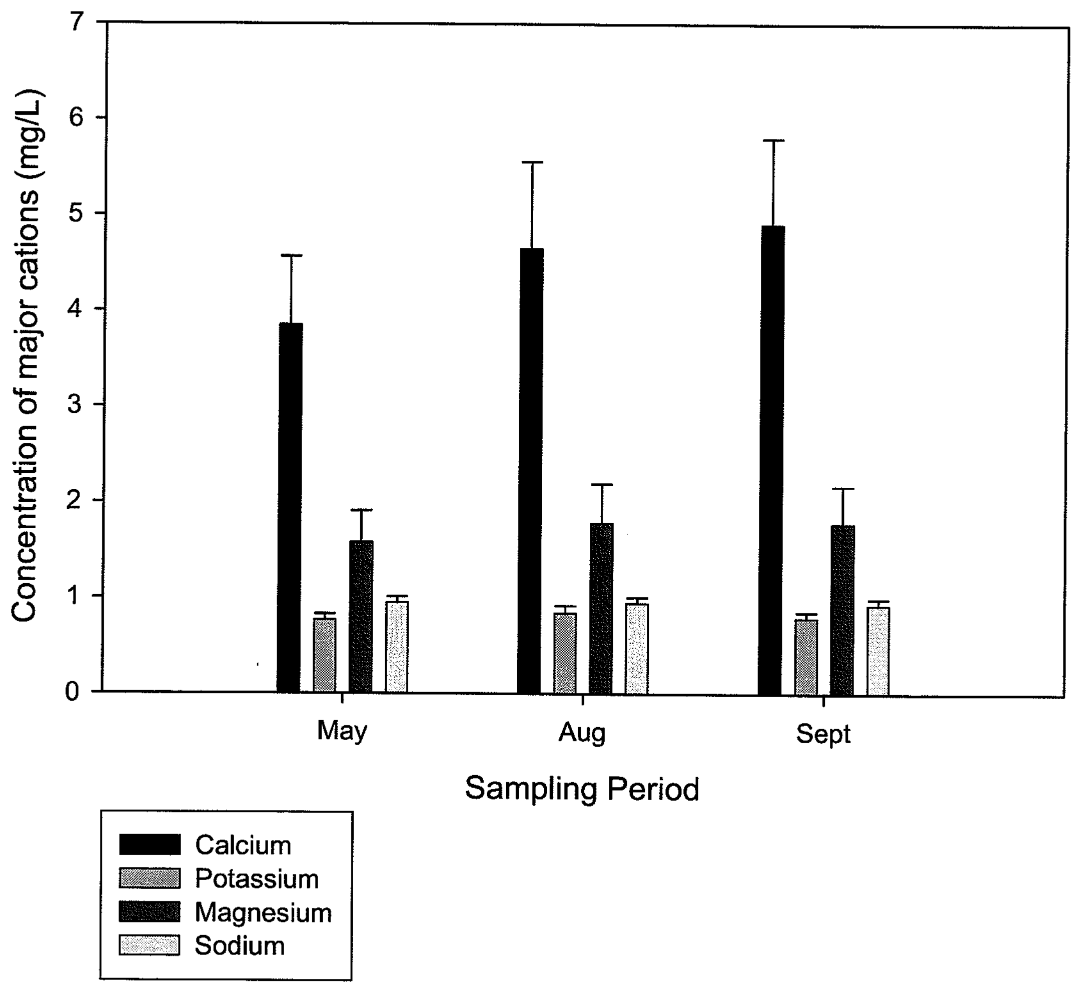

Figure 23: Mean 2005 seasonal concentration of major cations

± the standard error

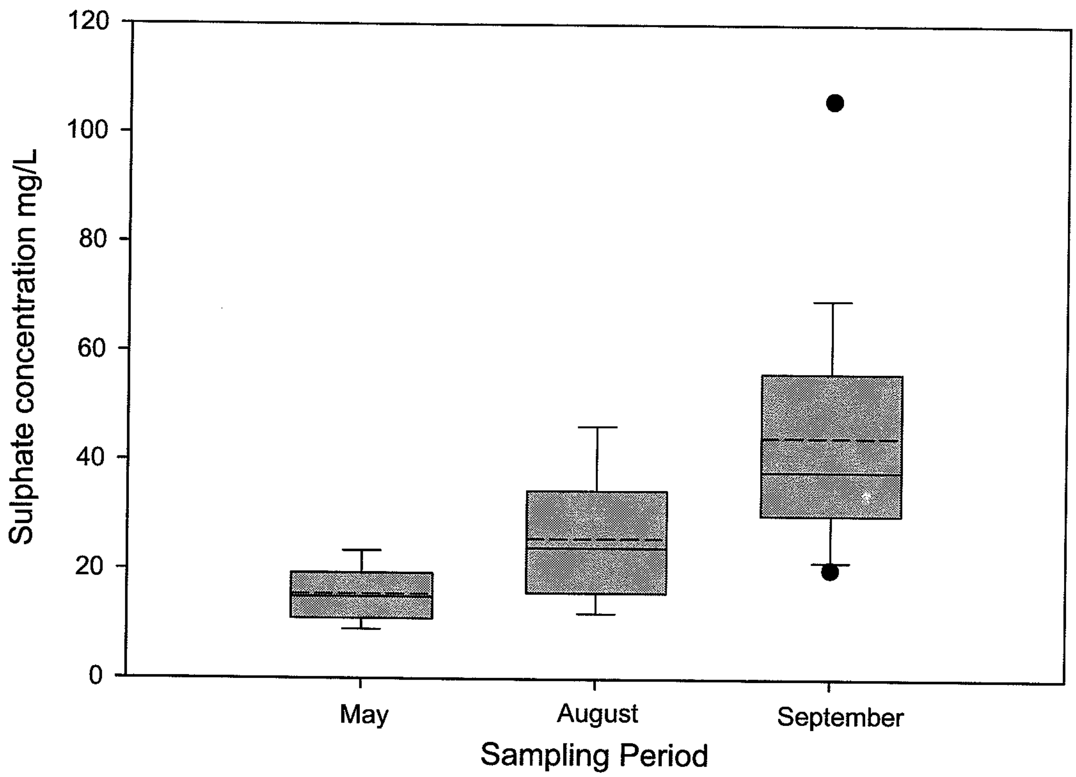

Figure 24: Seasonal 2005 Sulphate concentrations

Box plots represent median sulphate concentration (solid line), mean (dashed line) 10^{th} and 25^{th} 70^{th} and 90^{th} percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers.

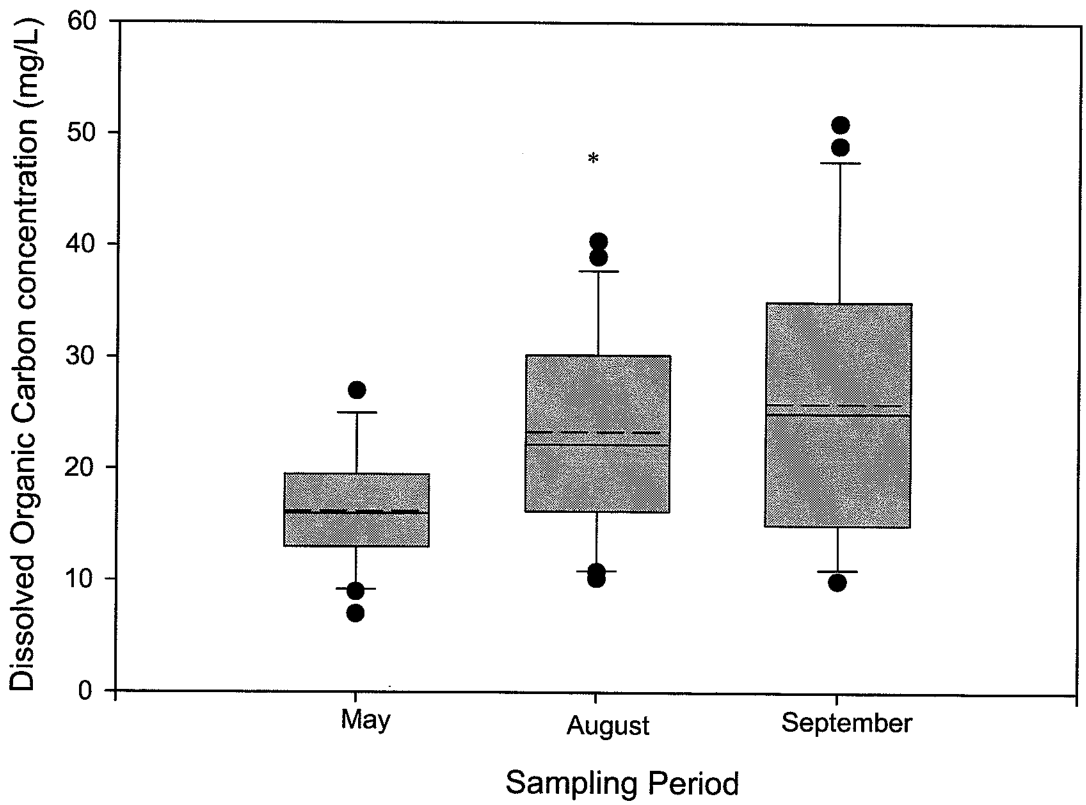

Figure 25: Seasonal Dissolved Organic Carbon concentrations
Box plots represent median DOC concentration (solid line), mean (dashed line) 10^{th} and 25^{th} 70^{th} and 90^{th} percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers.

4.7 Comparison between 2004 and 2005

A change in analytical labs used and different techniques of analysis make direct comparison of 2004 and 2005 data difficult. Total dissolved phosphorus, and total phosphorus were generally higher in lakes sampled in 2005 versus the same lakes sampled in 2004 (Figure 28). Total nitrogen concentrations showed the same trend

(Figure 29). Dissolved organic carbon also followed this result. (Figure 31). Conductivity and sodium concentration were significantly higher in 2004 than 2005 ($p= 0.0001$ and $p=0.003$) respectively while potassium ($p= .10$), calcium $p=0.54$, magnesium $p=0.64$) did not differ appreciably from 2004 to 2005. Average chlorophyll *a* concentrations in August 2005 were more than triple the concentrations in the same lakes sampled in 2004 (Figure 30). Average chlorophyll concentrations in the year 2005 were 27.6 μg/L and 9.2 μg/L for the same period in 2004 (Figure 30).

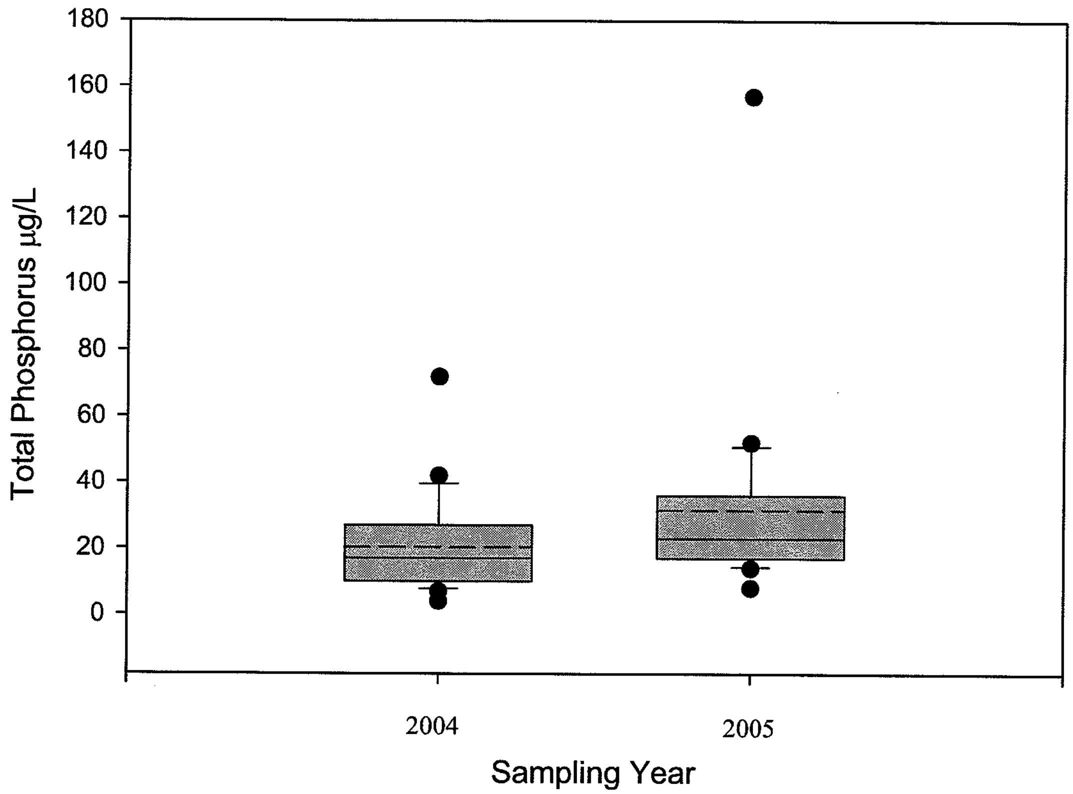

Figure 26: Comparison between 2004 and 2005 Total phosphorus concentrations Sampled July 26 to August 11th 2004 and August 8th to August 12, 2005.
Box plots represent median total phosphorus concentration (solid line), mean (dashed line) 10th and 25th 70th and 90th percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers. Concentrations in 2005 of total phosphorus were significantly higher than 2004 (p= 0.004).

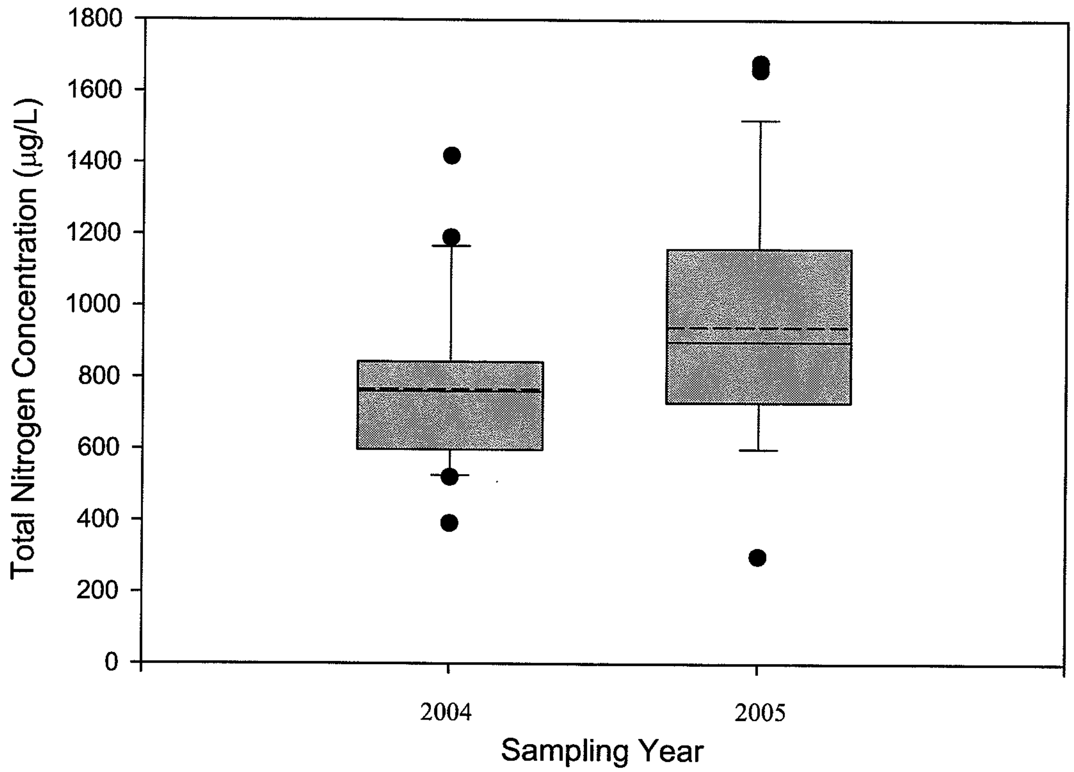

Figure 27: Comparison between 2004 and 2005 Total nitrogen concentrations Sampled July 26 to August 11th 2004 and August 8th to August 12, 2005.

Box plots represent median total nitrogen concentration (solid line), mean (dashed line) 10th and 25th 70th and 90th percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers. Concentrations in 2005 of total nitrogen were significantly higher than 2004 ($p < 0.001$).

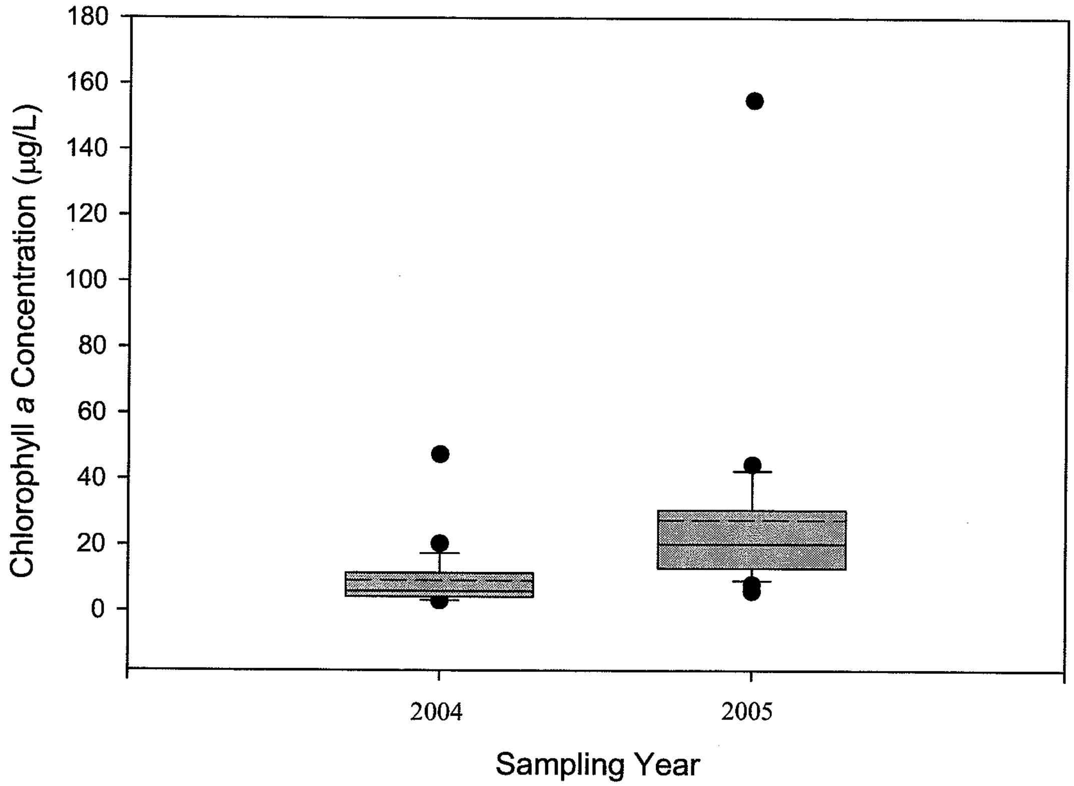

Figure 28: Comparison between 2004 and 2005 Chlorophyll a concentrations Sampled July 26 to August 11th 2004 and August 8th to August 12, 2005.

Box plots represent median total chlorophyll *a* concentration (solid line), mean (dashed line) 10th and 25th 70th and 90th percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers. Concentrations of chlorophyll *a* in 2005 were significantly higher than 2004 ($p<0.001$).

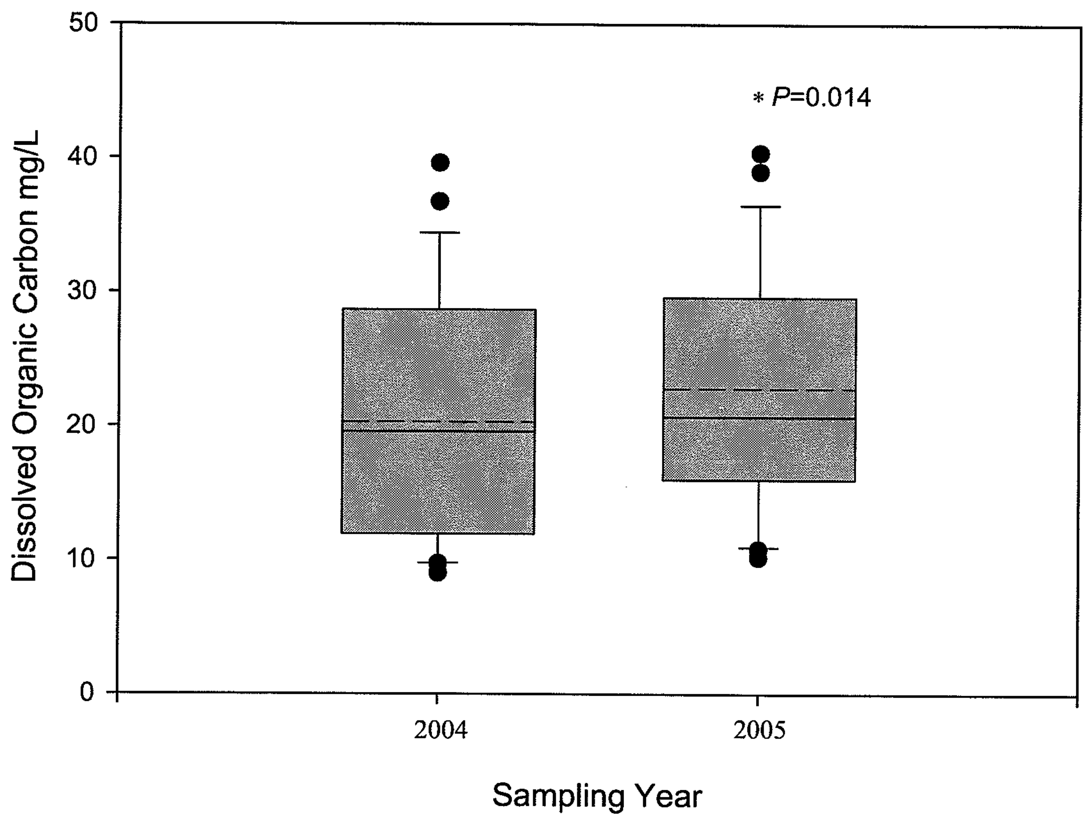

Figure 29: Comparison between 2004 and 2005 DOC concentrations
Water sampled July 26 to August 11th 2004 and August 8th to August 12, 2005.
Box plots represent median total DOC concentration (solid line), mean (dashed line) 10th and 25th 70th and 90th percentiles. Points on extreme top and bottom of box plot represents extreme high and low outliers. Concentrations of chlorophyll a in 2005 were significantly higher than 2004 (p=0.014).

4.8 Relationships between Watershed Features and Water Quality

4.8.1 Watershed Size

Watershed size was positively correlated with many key water quality variables though none of these correlations were statistically significant (Table 23).

4.8.2 Soil Type

Soils in the study area are mapped at a very coarse scale (1:100,000). The primary surficial geology of most of the study watersheds is bedrock. Lakes were classified based on the predominance of either bedrock or deep organic and/or deep basin (BD) soils into three categories. Catchments with greater than 50 percent deep basin and/ or organic soils, catchments with approximately 20-50 percent deep basin or organic soils, and catchments with over 80 percent bedrock. However, only five out the 74 watersheds not originating in Ontario[1] were not dominated by bedrock soil (Table 14). These included Okimaw Lake, Lake 96, Gold Lake and the Dawson and Boulette watersheds. A number of the study watersheds had approximately 50 percent bedrock. These lakes included Saxton, 82 and 83, English, Little Beaver, Shallow, Wanipigow and Happy. Watersheds dominated with deep basin and or organic soils had the highest average concentration of DOC in lake water (Table 24). On average, total nitrogen and total phosphorus concentrations were also higher in lakes with deep basin and or organic soils than in lakes with watersheds dominated by bedrock soils. Lakes with watersheds having 50 percent or more deep basin and or organic soils had the highest concentrations of nutrients on

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[1] Due to missing GIS data for watersheds originating in Ontario these watersheds were removed from the watershed analysis.

average. The mean was highly affected by Saxton Lake, which had high concentrations of nitrogen and phosphorus. Lakes with bedrock-dominated watersheds typically had the lowest concentrations of DOC, total nitrogen and total phosphorus; this is the same result as Kotak et al. (2005) found when examining streams of region. There were some exceptions to this rule. For example, Badou Lake, Owl Lake and Farrington Lakes all had elevated concentrations of DOC, TP and TN relative to the mean despite having a low proportion of deep basin or organic soils. However, the watersheds of these lakes were subject to harvesting disturbance of 11 percent to 37 percent of their watershed areas. In fact, of the lakes having 50 percent or more organic or deep basin soils, ten out of twelve watersheds have been subject to either forest fire or forest harvesting disturbance (Table 14).

Table 23: Pearson product moment correlation coefficients (*r*) and *P* values between watershed size and various water quality parameters measured in 2004.

Water Quality Parameter	r	P value
Secchi Depth	-0.17	NS
NO_3	0.25	NS
TDN	0.25	NS
TN	0.17	NS
TDP	0.28	NS
TP	0.16	NS
DOC	0.17	NS
Chlorophyll *a*	-0.03	NS
SO_4	-0.04	NS
PH	0.18	NS
Alkalinity	0.17	NS
Ca	0.15	NS
Conductivity	0.15	NS

P values: NS= not statistically significant (P>.10),
*=P<.10, ** P<0.05, *** P<.01

Table 24: Summary of 2004 water quality in lakes grouped by dominant soil type

Greater than 80% bedrock (n=58), 20-50% deep basin or organic soil (n=9), Over 50% deep basin or organic soil (n=6)

		Greater than 80% bedrock			20-50% deep basin or organic			Over 50% deep basin or organic		
Parameter	units	mean	min	max	mean	min	max	mean	min	max
Secchi	m	1.56	0.42	4.84	1.18	0.76	1.80	1.19	0.92	1.71
Photic	m	3.54	0.85	9.32	2.36	1.28	5.25	2.01	1.22	2.85
Nitrate/ Nitrite	μg/L	4	<1	36	14	1	75	6	<1	24
SUSP N	μg/L	157	58	459	196	89	674	204	98	294
TDN	μg/L	556	300	950	741	525	915	698	565	770
TN	μg/L	713	392	1191	937	616	1419	902	788	996
SUSP P	μg/L	11	4	30	18	6	65	14	9	24
TDP	μg/L	5	<1	21	9	6	16	9	<1	14
TP	μg/L	17	4	42	27	15	72	23	10	37
DOC	mg/L	18	9	40	24	18	33	23	14	31
CHL *a*	μg/L	7.13	2.09	27.73	10.45	2.84	47.48	8.79	3.89	18.52
SR Silica	mg/L	0.77	0.04	2.36	1.37	0.28	2.24	0.74	0.16	1.72
Chloride	mg/L	0.30	0.07	1.75	0.64	0.11	2.51	0.24	0.08	0.42
Sulphate	mg/L	1.30	0.42	6.31	0.76	0.16	1.80	0.65	0.46	0.94
Conductivity	μs/cm	38	18	154	77	27	175	36	26	47
Sodium	mg/L	1.11	0.52	9.25	1.45	0.84	2.74	1.02	0.76	1.13
Potassium	mg/L	0.70	0.20	3.35	0.80	0.35	1.26	0.81	0.58	1.19
Magnesium	mg/L	1.50	0.67	6.20	4.17	1.45	9.50	1.85	1.24	2.50
Calcium	mg/L	4.42	1.85	23.20	9.30	3.25	22.10	4.15	3.15	5.26
Alkalinity	mg/L	261	80	1440	675	126	1740	252	146	353

The relationship between lake water quality and soil type was also evaluated through correlation (Table 25). The categories bedrock (BR), deep basin (DB), organic deposits, glacial fluvial deposits (GD) and glacial till (T3) were used to plot soil type against water quality parameters. One watershed had glacial till soil and only three watersheds had soil composed of fluvial deposits. In all instances, the proportions of these soil types were small (less than five percent). Given that statistical analysis on such few data points is questionable, these soil types were removed from the analysis.

Table 25: Pearson product moment correlation coefficients and P values between soil type and various water quality parameters

Water Quality Parameter	Soil Type					
	BR		OD		DB	
Secchi Depth	0.07	NS	-0.18	NS	-0.10	NS
TDN	-0.27	***	0.31	***	0.22	*
TN	-0.29	***	0.16	NS	0.34	***
TDP	-0.14	**	0.27	**	0.03	NS
TP	-0.18	***	0.05	NS	0.25	**
DOC	-0.17	**	0.31	***	0.08	NS
Chlorophyll a	-0.10	NS	-0.09	NS	0.23	*
Sulphate	0.15	NS	-0.18	NS	-0.19	NS
PH	-0.03	NS	0.04	NS	0.00	NS
Alkalinity	-0.19	**	-0.02	NS	0.23	*
Calcium	-0.15	NS	-0.00	NS	0.17	NS
Conductivity	-0.17	**	-0.02	NS	0.20	*

P values: NS= not statistically significant (P>.10),
*=P<.10, ** P<0.05, *** P<.01

Though the correlation coefficients were not particularly strong between any one soil type and water quality parameter, several trends can be observed. Dissolved and total nitrogen, and phosphorus were negatively correlated with bedrock soils and positively correlated with deep basin and/or organic soils (Table 25). Organic soils were correlated with higher concentrations of dissolved organic carbon and, conversely, decreasing Secchi depth; however, only the trend with DOC was statistically significant. Chlorophyll *a* and alkalinity were positively correlated with deep basin soils, and alkalinity was negatively associated with bedrock soils.

4.8.3 Forest Type

When examining the relationship between FRI characteristics and water quality parameters, several trends are evident (Table 26). Total dissolved nitrogen, dissolved phosphorus and dissolved organic carbon was strongly correlated with the proportion of wetlands in a watershed. Secchi depth was negatively correlated with proportion of wetlands in a watershed; that is, as wetland proportion increased, the water clarity decreased. The proportion of jack pine in a watershed was negatively correlated with nitrogen and phosphorus, DOC, conductivity, and calcium. The proportion of black spruce was weakly associated with most water quality parameters. Hardwood tree species were positively correlated with suspended nitrogen, suspended phosphorus and alkalinity.

Table 26: Pearson product moment correlation coefficients and P values between Stand Type from the Forest Resource Inventory and various water quality parameters.

	Forest Resource Inventory Stand Type Group							
Parameter	Jack Pine		Black Spruce		Hardwoods		Wetlands	
Secchi Depth	-0.03	NS	-0.06	NS	0.03	NS	-0.49	***
TDN	-0.29	**	0.09	NS	-0.06	NS	0.56	***
Suspended N	-0.16	NS	0.23	**	0.29	**	-0.08	NS
TN	-0.30	***	0.18	NS	0.09	NS	0.39	***
TDP	-0.22	*	-0.10	NS	0.21	*	0.44	***
Suspended P	-0.19	NS	0.13	NS	0.29	**	0.08	NS
TP	-0.24	**	0.06	NS	0.31	***	0.24	***
DOC	-0.19	NS	-0.06	NS	-0.23	**	0.66	***
Chlorophyll a	-0.25	**	0.14	NS	0.15	NS	0.02	NS
SO4	0.07	NS	0.06	NS	-0.06	NS	-0.35	***
pH	0.01	NS	-0.04	NS	0.12	NS	-0.16	NS
Alkalinity	-0.30	***	0.17	NS	0.23	**	-0.17	NS
Ca	-0.28	**	0.16	NS	0.18	NS	-0.12	NS
Conductivity	-0.29	**	0.16	NS	0.19	NS	-0.16	NS

P values: NS= not statistically significant (P>.10),
*=P<.10, ** P<0.05, *** P<.01

Table 24 supports correlations seen in the soils data; that is, watersheds dominated by rocky outcrops and bedrock soils, which are also conducive to jack pine forests, have lower concentrations of most water quality constituents. Hardwood stands and wetlands, in particular, appear to be associated with higher nutrient concentrations in lake water. Again, hardwood tree species are more conducive to grow on better-developed deep basin that are more nutrient-rich and contribute more nitrogen, phosphorus, calcium, and alkalinity through the watershed to lake water. The proportion of wetlands in a watershed was strongly correlated with concentrations of dissolved organic carbon, total dissolved nitrogen and total dissolved phosphorus (Table 26, Figure 32 and 33). It appears that wetland area and forest type (hardwoods versus softwoods, itself representative of soil conditions) in a watershed is an important factor in determining the overall water quality of a lake regardless of watershed disturbance.

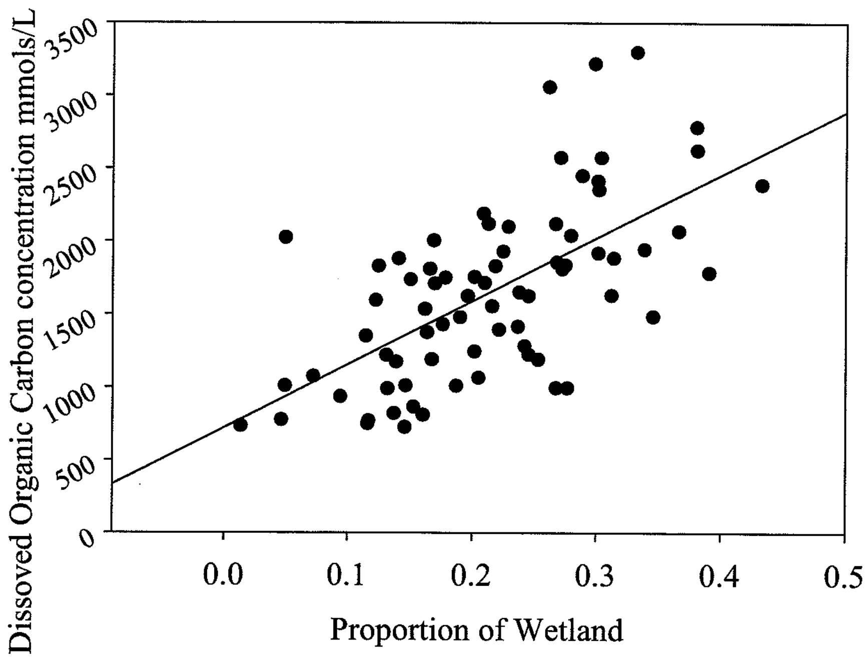

Figure 30: The relationship between wetland proportion in a watershed and concentration of dissolved organic carbon observed from 74 lakes of the Eastern Manitoba Boreal Shield.

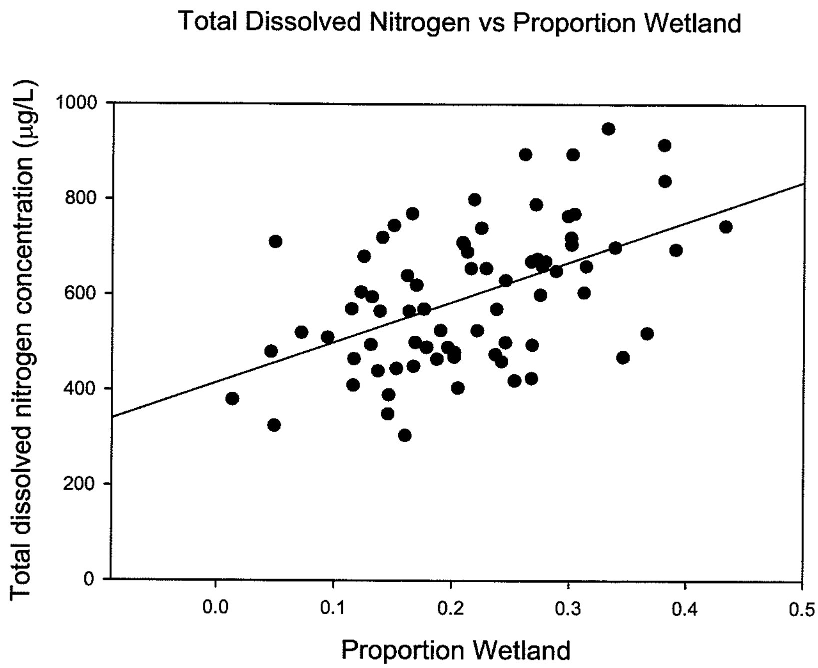

Figure 31: The relationship between wetland proportion in a watershed and concentration of total dissolved nitrogen observed from 74 lakes of the Eastern Manitoba Boreal Shield.

4.8.4 Disturbance

Water quality results indicate that landscape disturbance had a marked influence on lake water quality. Lakes with forest fire and forest harvesting had higher concentrations of most chemical water quality parameters. This was particularly true when evaluating lakes with forest fires within the last 15 years and harvests older than 15 years. (Figures 34 to 39, Table 26).

4.8.5 Insect Outbreaks

Insect outbreaks documented in the GIS data were restricted to the Wanipigow

Lake watershed and further south. Most watersheds did not have any documented evidence of spruce budworm or forest tent caterpillar. In fact, only 18 of the 74 non-Ontario originating watersheds had outbreaks of spruce budworms and/or forest tent caterpillars. In many cases, these watersheds were subject to repeat insect disturbance totalling greater than 100 percent of the watershed area. With respect to water quality, these lakes had higher than average concentrations of all water quality parameters when compared to the overall set of lakes (Table 27). In addition, in the past thirty-five years, these watersheds were also subject to forest harvesting on an average of 24 percent of their watershed areas. These watersheds however may have a greater abundance of hardwood tree species and differences in ion chemistry in the lakes of these watersheds may be due to differences in soil and forest type than insect damage exclusively.

Table 27: Pearson product moment correlation coefficients and P values between the proportion of a watershed disturbed by spruce budworms and forest tent caterpillars

Water Quality Parameter	Proportion Insect Damage	
	r	*P value*
TDN	0.14	NS
TN	0.22	*
TDP	0.11	NS
TP	0.11	NS
DOC	0.08	NS
Chlorophyll *a*	0.21	*
Conductivity	0.54	***
Calcium	0.55	***
Magnesium	0.34	**
Potassium	0.42	***
Sodium	0.32	***

P values: NS= not statistically significant (P>.10), *=P<.10, ** P<0.05, *** P<.01

4.8.6 The Effects of Forest Fire and Forest Harvesting on Water Quality

Recent fires (within the last five years) were restricted to the north of the study area where there was no forest harvesting. These recent fires burned on average 45 percent of the watershed areas. Forest harvesting within the last 15 years have been limited to an average area of 15 percent of the affected watersheds whereas harvests within the last five years were limited to an average of 5 percent of the watershed area. Water quality in lakes with older watershed harvests (older than 20 years) showed the greatest differences with respect to reference systems (Figures 34 to 39). Lakes with the majority of watershed harvesting 20 years old or older contained, on average, the highest concentrations of total nitrogen, total phosphorus, dissolved organic carbon, chlorophyll *a,* and calcium (Figures 34 to 39). Conductivity was also highest in these historically harvested systems. When considering watershed fire within the last 50 years, total nitrogen, total phosphorus, dissolved organic carbon, chlorophyll *a,* calcium and conductivity were all elevated in these lakes over reference systems. Mean total nitrogen, phosphorus, calcium, conductivity and chlorophyll *a* were higher in lakes affected by watershed harvesting than lakes affected by watershed fire, though these results were highly variable (Figures 34 to 39).

Total phosphorus concentration was significantly higher from reference systems in lakes with harvested and burned watersheds ($p<0.05$); however, lakes with watershed fire and harvesting were not significantly different from each other ($p>0.05$). Dissolved organic carbon concentration was significantly higher in lakes with watershed harvesting than reference lakes (Figure 36). Lakes with watershed fire and both harvesting and fire also had high concentrations of DOC that were not significantly different from lakes with harvested watersheds (p>0.05). Conductivity and concentrations of chlorophyll *a* and calcium were also significantly higher in lakes with watershed harvesting (Figures 37 and 38).

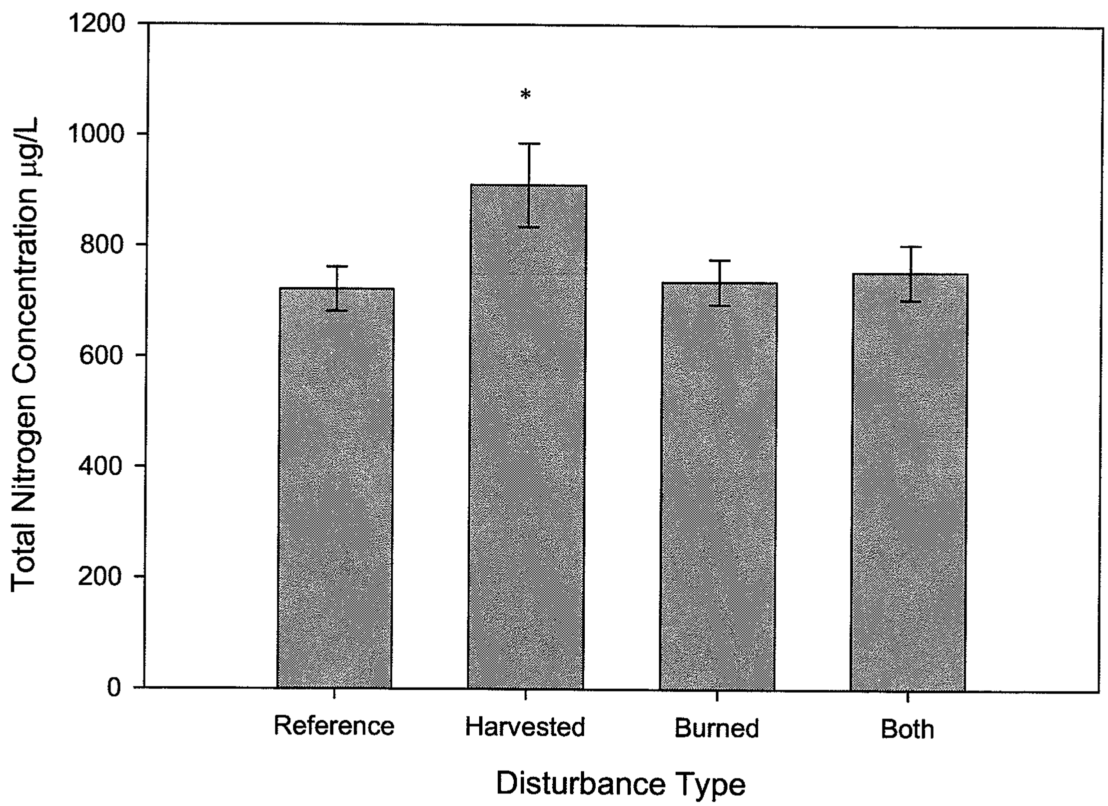

Figure 32: Mean total nitrogen concentrations in 2004 for lakes grouped by disturbance type. Note reference, (n=25) harvested (n=10), burned (n=23) harvested and burned (n=9) watersheds Vertical bars are standard errors ± of means. The total nitrogen concentration was significantly higher in lakes with harvested watersheds (*= P<0.05).

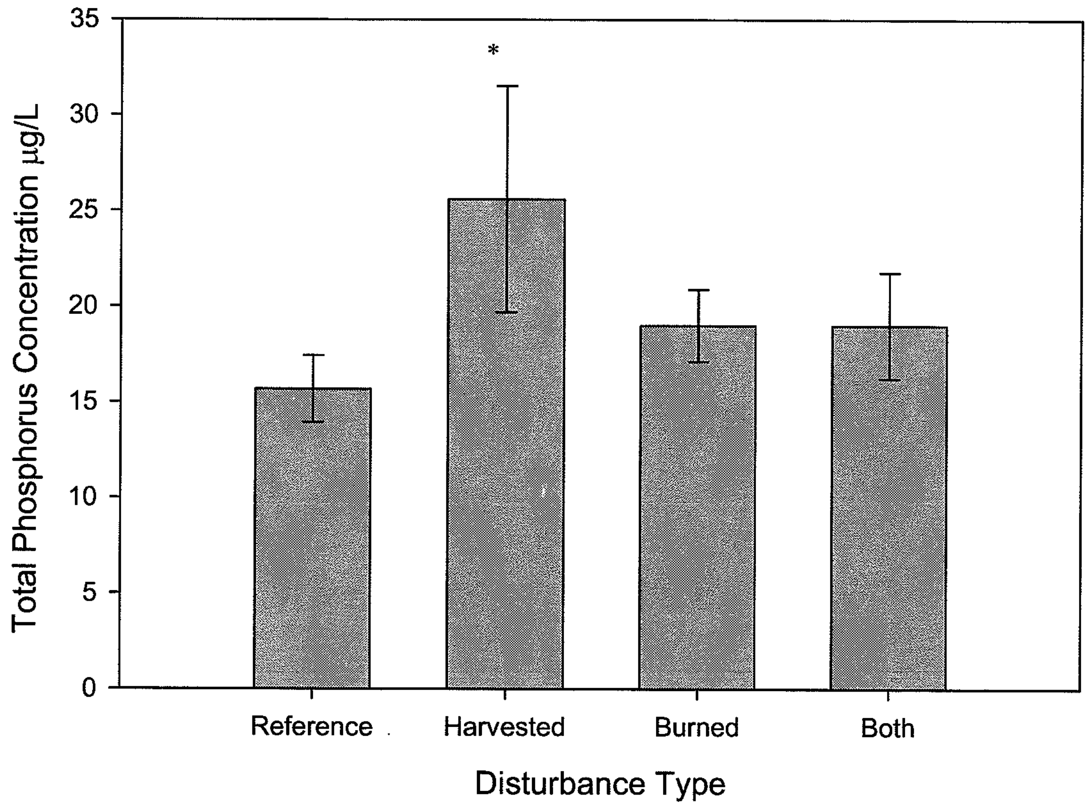

Figure 33: Mean total phosphorus concentrations in 2004 for lakes grouped by disturbance type. Note: reference, (n=25) harvested (n=10), burned (n=23) harvested and burned (n=9) watersheds: Vertical bars are standard errors ± of means. Total phosphorus was significantly higher in lakes with harvested watersheds (*= P<0.05).

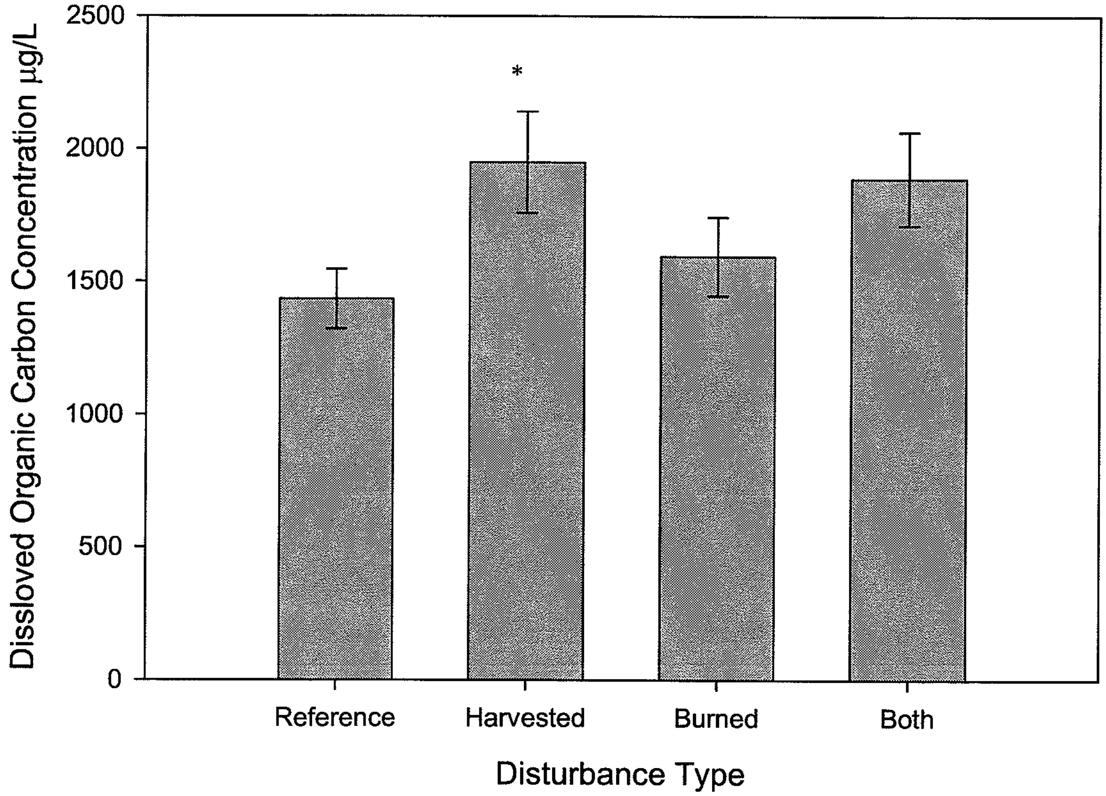

Figure 34: Mean DOC concentrations in 2004 for lakes grouped by disturbance type.
Note: reference, (n=25) harvested (n=10), burned (n=23) harvested and burned (n=9) watersheds: Vertical bars are standard errors ± of means. DOC was significantly higher in lakes with harvested watersheds (*= P<0.05).

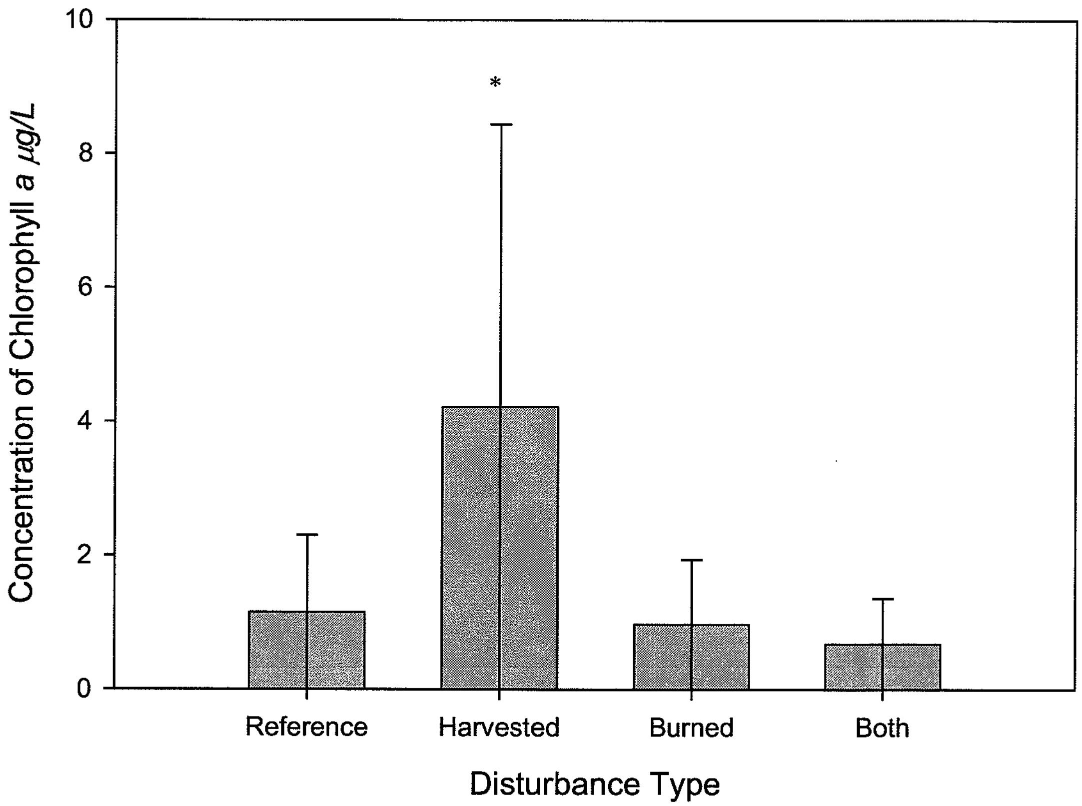

Figure 35: Mean chlorophyll *a* concentrations in 2004 for lakes grouped by disturbance type. Note: reference, (n=25) harvested (n=10), burned (n=23) harvested and burned (n=9) watersheds: Vertical bars are standard errors ± of means. Chlorophyll *a* was significantly higher in lakes with harvested watersheds (*= P<0.05).

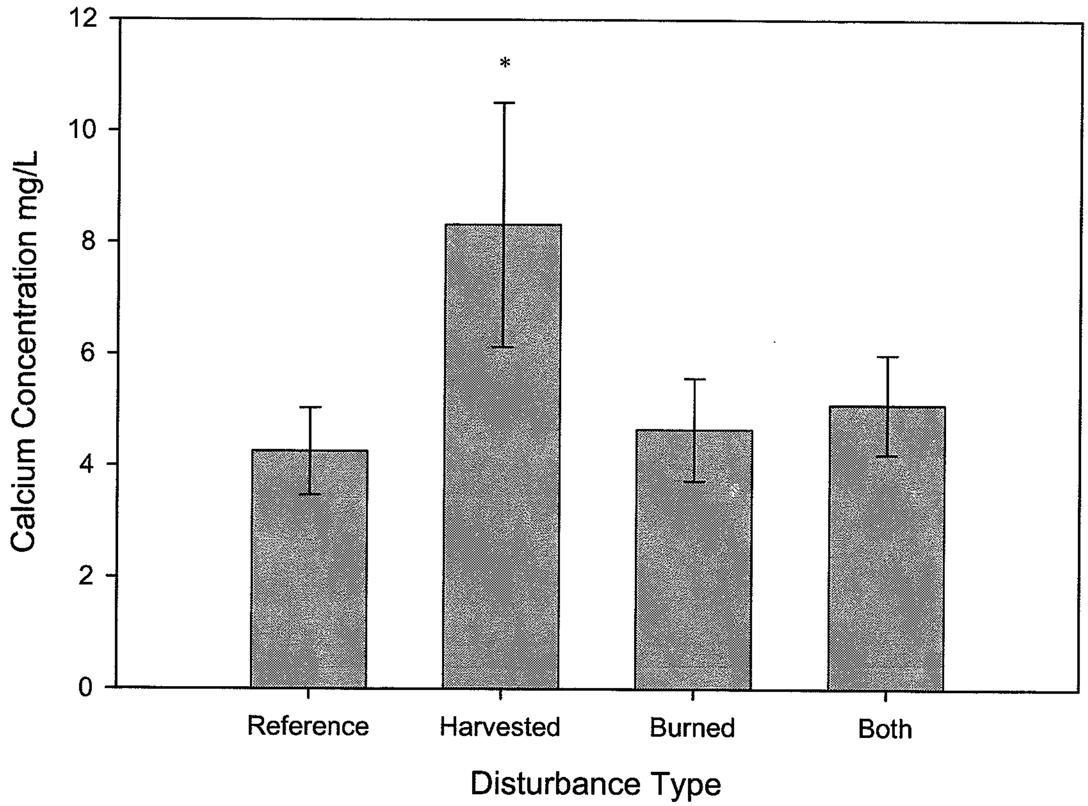

Figure 36: Mean calcium concentrations in 2004 for lakes grouped by disturbance type. Note: reference, (n=25) harvested (n=10), burned (n=23) harvested and burned (n=9) watersheds: Vertical bars are standard error ± of means.

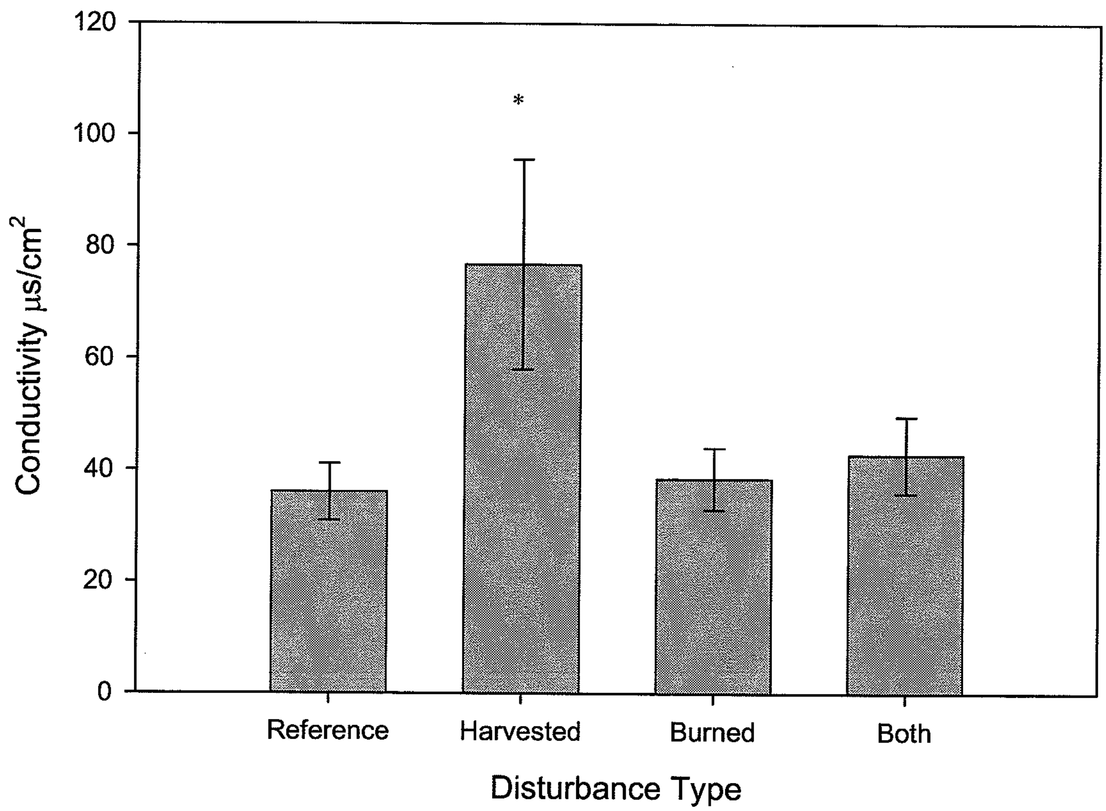

Figure 37: Mean conductivity in 2004 for lakes grouped by disturbance type
Note: reference, (n=25) harvested (n=10), burned (n=23) harvested and burned (n=9) watersheds Vertical bars are standard error ± of means. Conductivity was significantly higher in lakes with harvested watersheds (*= P<0.05).

Correlation analysis indicated that the relationship between the cumulative proportion of a watershed disturbed by forest fire within the last 35 years and key water quality parameters was markedly different from that observed with forest harvesting during the same period (Table 28). While the proportion burned by forest fire within the last 15 years was positively correlated with dissolved and total phosphorus, this did not hold true for older fires. In fact, with respect to forest fire other than phosphorus, there were no significant correlations between the proportions of a watershed burned and key water quality variables. The cumulative proportion of forest harvested during the last five years was not significantly correlated with any water quality variables. On the other hand, correlations between several water quality variables and the cumulative proportion of forest harvested within the last 15, 35 and 50 years were significant (Table 28).

Table 28: Pearson product-moment correlation coefficients and *P* values between various water quality parameters and the cumulative proportion of a watershed disturbed by logging or fire within the last 5, 15, 35 and 50 years

Parameter	**Forest Fire**								**Harvesting**							
	Last 5		**Last 15**		**Last 35**		**Last 50**		**Last 5**		**Last 15**		**Last 35**		**Last 50**	
Secchi Depth	0.07	NS	-0.03	NS	0.16	NS	0.16	NS	-0.17	NS	-0.12	NS	-0.17	NS	-0.18	NS
TDN	-0.02	NS	0.06	NS	-0.17	NS	-0.17	NS	-0.02	NS	0.20	*	0.26	**	0.27	**
TN	-0.16	NS	0.13	NS	-0.15	NS	-0.15	NS	-0.06	NS	0.27	**	0.33	***	0.33	***
TDP	-0.03	NS	0.28	**	-0.10	NS	-0.10	NS	-0.08	NS	0.01	NS	0.16	NS	0.17	NS
TP	0.00	NS	0.24	**	-0.11	NS	-0.11	NS	-0.09	NS	0.26	**	0.31	***	0.31	***
DOC	-0.24	**	0.00	NS	-0.17	NS	-0.17	NS	0.15	NS	0.16	NS	0.18	NS	0.19	*
SO4	-0.01	NS	-0.14	NS	-0.02	NS	-0.02	NS	-0.07	NS	-0.16	NS	0.20	*	0.18	NS
pH	-0.06	NS	0.04	NS	0.07	NS	0.07	NS	-0.14	NS	0.11	NS	0.20	*	0.19	*
Ca	-0.17	NS	-0.06	NS	0.01	NS	0.01	NS	-0.11	NS	0.43	***	0.41	***	0.41	***
Alkalinity	-0.16	NS	-0.03	NS	0.03	NS	0.03	NS	-0.13	NS	0.50	***	0.47	***	0.46	***
Conductivity	-0.16	NS	-0.04	NS	0.02	NS	0.02	NS	-0.11	NS	0.46	***	0.49	***	0.49	***
Chlorophyll a	-0.04	NS	0.16	NS	-0.08	NS	-0.08	NS	-0.02	NS	0.31	***	0.30	***	0.29	**

P values: NS= not statistically significant (P>.10), *=P<.10, ** P<0.05, *** P<.01

4.8.7 Mechanical Site Preparation

In the study area, only eleven watersheds were subject to soil preparation with an average of three percent of the area of each prepared watershed. The small number of watersheds with site preparation made it impossible to separate possible harvesting effects from site preparation; thus, a statistical analysis of the effects of mechanical site preparation in watersheds on the water quality of the region was not done.

4.8.8 Linear Features

Only 38 out of the 74 watersheds not originating in Ontario had any linear features such as roads, power lines, and trails. There were no linear features in Atikaki Wilderness Park. Linear features in these watersheds were not associated with most water quality parameters (Table 29).

Table 29: Pearson product-moment correlation coefficients and *P* values between various water quality parameters and proportion of linear features (roads, power lines and trails) in a watershed

Water Quality Parameter	Km linear feature/Km^2 watershed	
Secchi Depth	0.01	NS
TDN	0.05	NS
TN	0.11	NS
TDP	-0.17	NS
TP	0.00	NS
DOC	-0.08	NS
SO4	0.00	NS
pH	-0.09	NS
Ca	0.15	NS
Alkalinity	0.12	NS
Conductivity	0.13	NS
Chlorophyll a	0.15	NS

P values: NS= not statistically significant (P>.10), *=P<.10, ** P<0.05, *** P<.01

4.9 Multivariate Statistical Analysis

4.9.1 2004 Data

Principle Component Analysis was used to compare lakes based on their water quality parameters (Figure 40). The Eigenvalues for axis one and axis two were 43.5 percent and 19.3 percent respectively which explained 62.8 percent of the variability in the data Most lakes had similar water chemistry and were situated near the middle of the ordination biplot. Nine lakes were identified as outliers located on the far right hand side of the ordination biplot. These included Saxton Lake, Bernic Lake, Little Beaver Lake, Badou Lake, Lake 56, Wanipigow Lake, Spence Lake, Stormy Lake and Dawson Lake. These lakes were positively correlated with axis one and had relatively high concentrations of chlorophyll *a* total phosphorus, conductivity, magnesium, sulphate and potassium. Of the above lakes, eight out the nine have a history of watershed fire, watershed harvesting or both. For example, Saxton Lake had 49 percent of its watershed harvested within the last 35 years. Bernic Lakes was 36 percent harvested within the last 30 years and had an active mine on its shore. Little Beaver Lake (Lake 71) had 50 percent of its watershed harvested within the last 35 years. Badou Lake (Lake 36) had 11 percent of its watershed harvested within the last 35 years. The watershed of Lake 56 was completely burned within the last 15 years. The Wanipigow Lake (L47) watershed was 10 percent harvested and 40 percent burned within the last 30 years. The Stormy Lake watershed (L35) was 17 percent burned within the last 35 years. Lastly, the Dawson Lake watershed was 95 percent burned within the last 15 years.

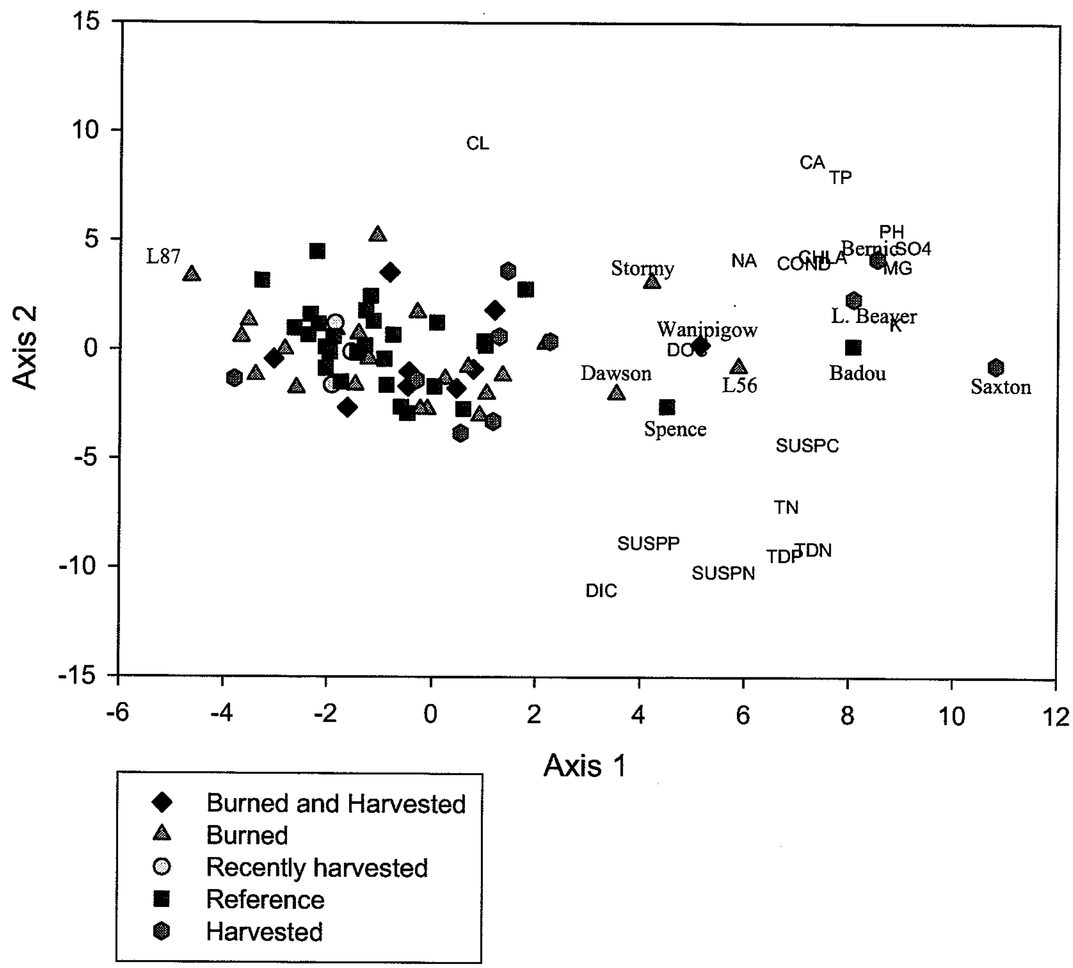

Figure 38: Principle component analysis biplot of 2004 water quality data. The Eigen values for axis 1 and axis 2 were 43.5 percent and 19.3 percent respectively.

Correspondence analysis was used to compare lake water quality to watershed features such as soil type, forest type, percentage wetlands and disturbance type. The correspondence biplot was highly influenced by the proportion of organic and/or deep basin soils and the proportion of hardwoods in a watershed which were both limited in the study area (Figure 41 and 42). The first and second axis accounted for 42 percent and 19.5 percent of the variation in the study lakes respectively. Most of the study lakes were associated with a high proportion of bedrock soils in the watershed and a high proportion of jack pine. Burned watersheds were together near the top of the correspondence analysis biplot (Figure 42). Harvested and reference watersheds showed considerable variability in their placement on the correspondence biplot, indicating the variability of the watershed soil conditions, disturbance history and lake water chemistry.

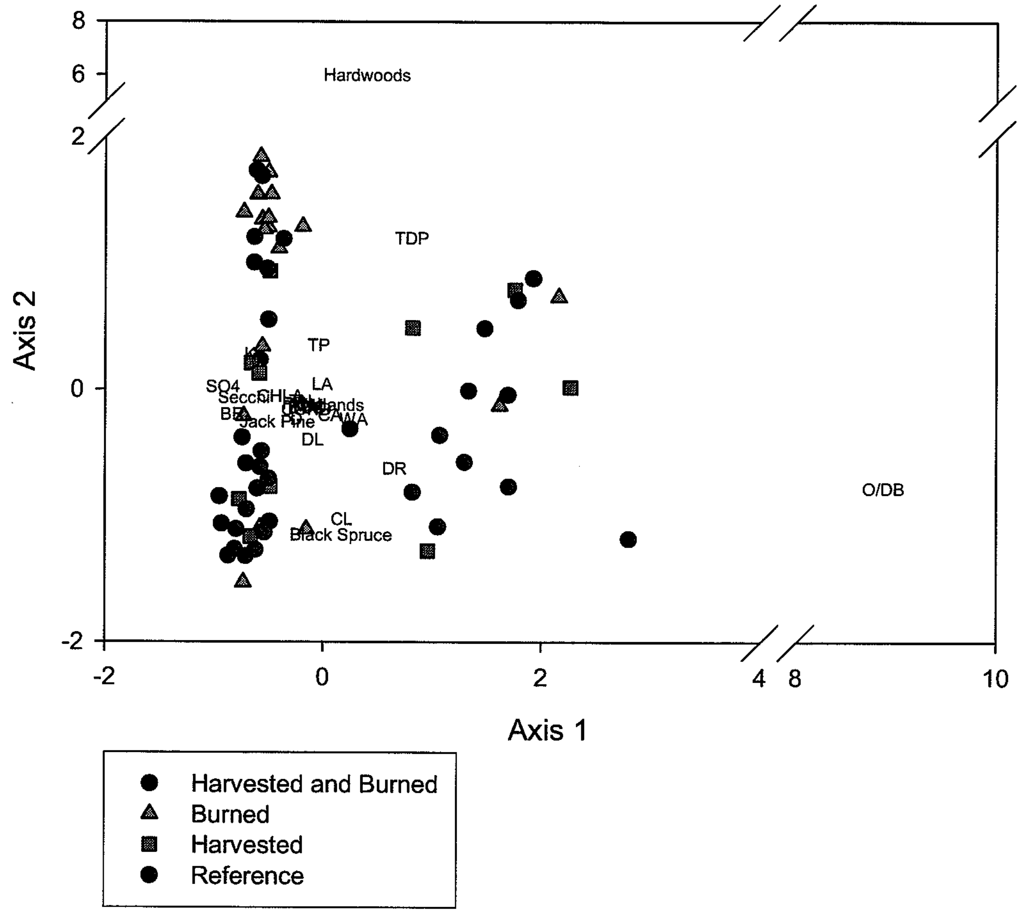

Figure 39: Correspondence analysis of soil type, watershed features and water quality. The first and second axis at 42 percent and 19.5 percent cumulatively account for 61 percent of the variation in the data. Note: BR (bedrock), DR (drainage ratio), WA (watershed area), LA (Lake area), DL (shoreline development), TDP (total dissolved phosphorus), TP (total phosphorus), CL (chloride), CHLA (chlorophyll a), Secchi (Secchi Depth), K (potassium).

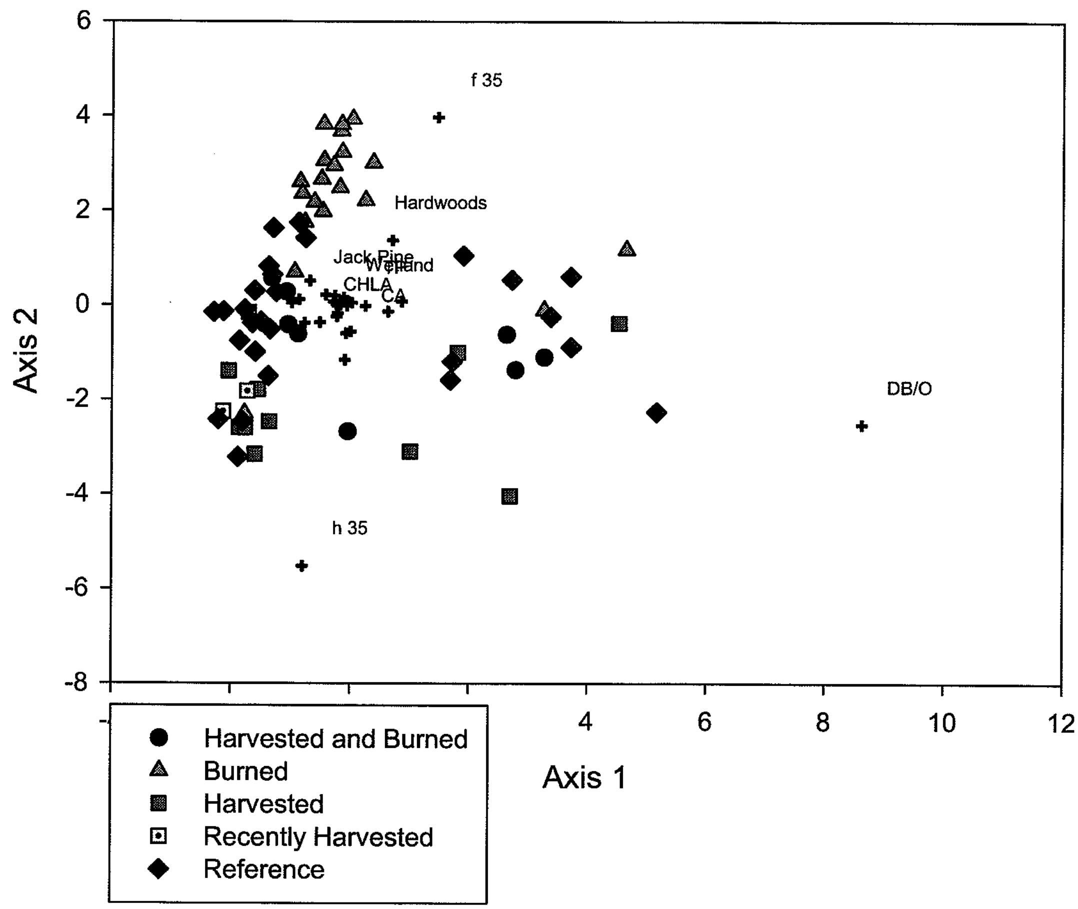

Figure 40: Correspondence analysis of water quality parameters and watershed features. Axis 1 explains 27.94 percent of the variation while Axis 2 explains 23.63 percent of the variation in the data. Note: h35 proportion of a watershed harvested within the last 35 years, f35 proportion of a watershed burned within the last 35 years. DB/O= proportion of a watershed with deep basin or organic soils. Chl = chlorophyll *a* concentration. Ca = Calcium concentration. Hardwoods = proportion of hardwood tree species in a watershed, Wetland = proportion of wetlands in a watershed. Jackpine= proportion of jackpine in a watershed. Overlapping variable labels close to origin removed from the biplot for clarification.

4.9.2 2005 data

Principle component analysis of 2005 water quality data explained 73 percent of the variation in the water chemistry data. The PCA biplot was strongly influenced by axis 1 which seems to correspond to a nutrient gradient. The PCA biplot was highly influenced by Saxton Lake which had the highest concentrations of most water chemistry variables. When Saxton Lake was removed and the analysis rerun, the first two axis accounted for 67 percent of the variation in the data at 47.1 percent and 19.6 percent for axis one and axis two respectively (Figure 42). With Saxton Lake removed from the analysis several trends became evident. May samples were typically further removed from total phosphorus, total dissolved phosphorus and total Kjeldahl nitrogen (Figure 44). August samples were closest to these parameters and thus had higher concentrations of phosphorus and nitrogen than May samples. September samples had intermediate N and P concentrations and were located between May and August samples on the ordination.

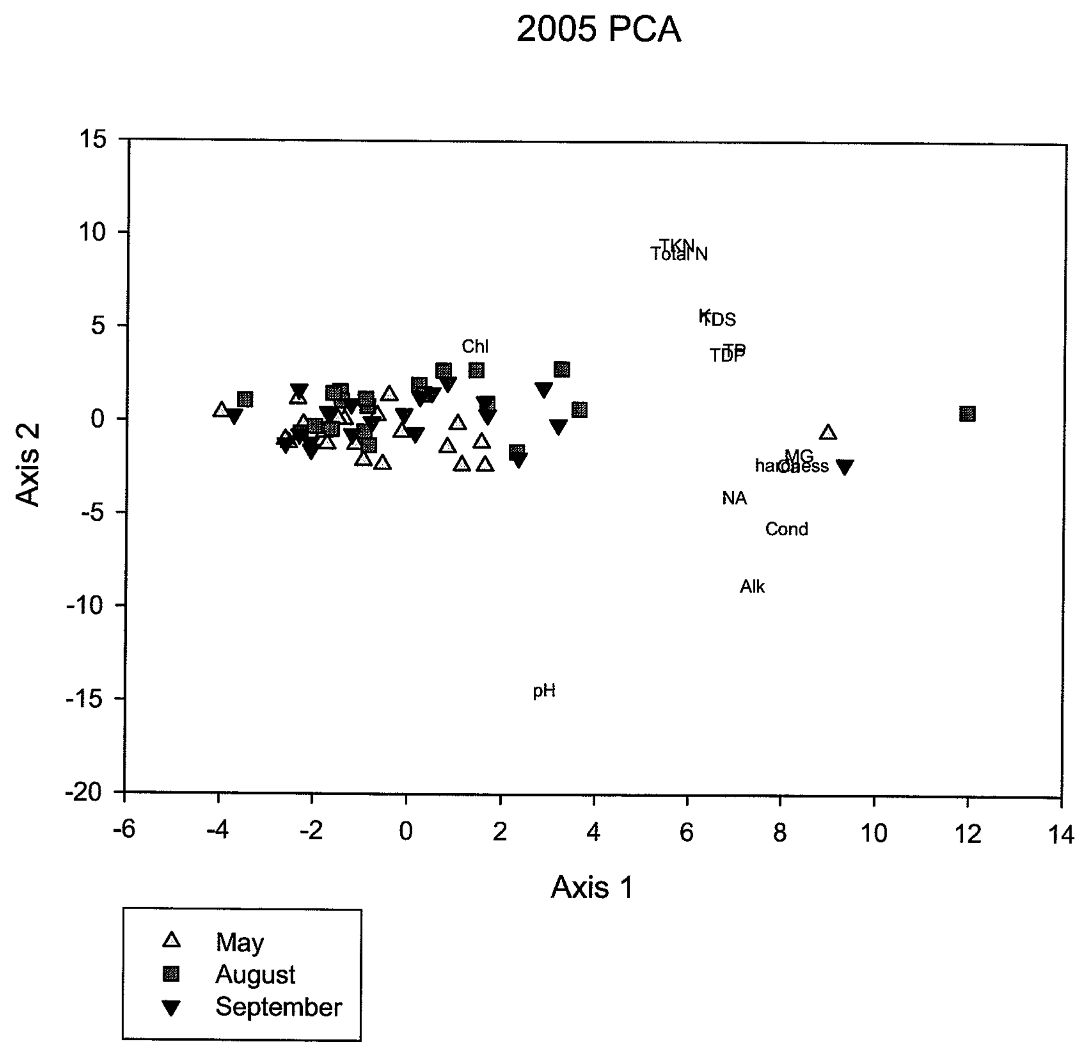

Figure 41: Principle component analysis of 2005 water quality data.

Axis 1 and Axis 2 explain 59.9 percent and 12.6 percent of the variation in the data respectively. Outlier on the right hand side is Saxton Lake (Lake 100).

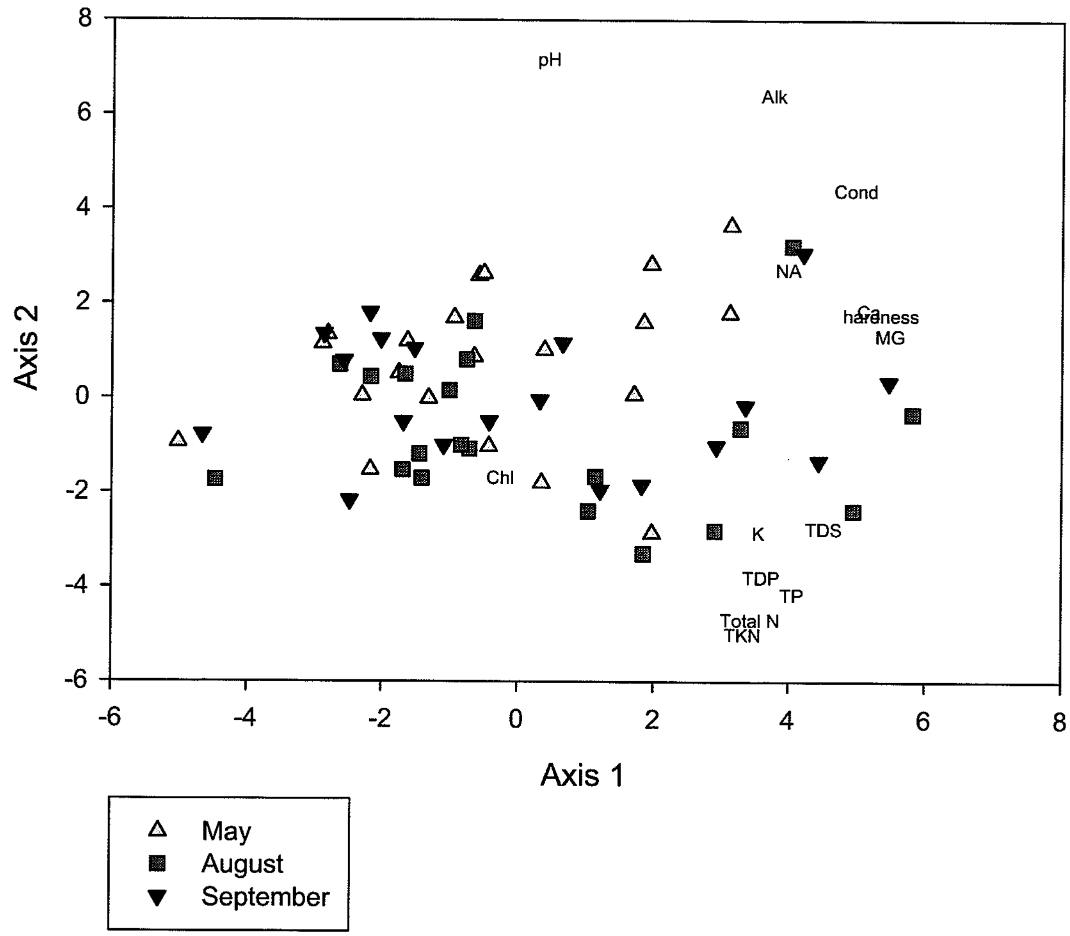

Figure 42: Principle component analysis of 2005 water quality data (Saxton Lake removed). Axis 1 and Axis 2 explain 47.1 percent and 19.6 percent of the variation in the data respectively. Saxton Lake (outlier identified in Figure 5.5 removed from the analysis).

Chapter 5: Discussion

5.1 Objective 1

5.1.1 Baseline Water Quality of the Region

The first objective was to obtain a broad understanding of baseline water quality in lakes on the east side of Lake Winnipeg. Most of the lakes have no previous water quality data. Lakes in the region are generally shallow, and oligotrophic to mesotrophic in nutrient status. This study has considerably increased the water quality data for this region of Manitoba. The data indicated there was considerable variability in lake size, watershed size, watershed features, disturbance history and water quality.

The dominant soil type in the region is bedrock and the dominant forest type is Jack Pine especially in northern and eastern watersheds. Further west and south, deep basin and organic soils become more common. This is the result of patterns left by the Wisconsin Glaciation. Further west and south, the landscape was affected by deeper Lake Aggassiz sediments, likely accounting for observed soil conditions today.

The majority of the study lakes, particularly in the north, have no road access and no industrial development. The lack of development and the remote nature of many of these lakes make the data collected valuable as baseline data. An example of the value of baseline data would be monitoring the effects of long-range transport of atmospheric pollutants and the effects of climate change or future watershed disturbance. Given that watershed fire is a common natural process in the region, it is likely that many of the reference watersheds will experience a certain amount of forest fire in the near future. Having baseline data provides for the comparison of lake water quality before and after watershed disturbance. Likewise, it is probable some of the reference watersheds not protected from resource related activity will experience watershed harvesting at some point in the near future. In fact, 19 of the study watersheds correspond with areas identified in Tembec's five-year operating plan as locations for timber harvesting (Table 30). These data provide a unique opportunity to monitor the effects of forest harvesting on water quality and the longevity of any associated impacts if any of these watersheds are subject to forest harvesting.

Most of the study lakes were relatively shallow with an average depth of approximately five meters. There were, however, a number of deeper lakes in the study area (e.g., Birse and Aikins Lake with maximum depths greater 20 and 90 meters respectively). Aikins Lake is the second deepest lake in Manitoba and has a circular shoreline consistent with a meteor impact. Many of the lakes could be considered wetlands, having mean water depths of less than two meters (National Wetlands Working Group 1997). Specifically, Gold Lake, L43, L74, Shallow, Clagula, L33 and Maskwa Lakes, with average depths around two meters, are Shallow Open Water under the Canadian System of Wetland Classification.

Sampling a single site in the centre of each lake provided an adequate initial characterization of its water quality. There is a trade off between sampling an extensive number of lakes infrequently as done in this study, and sampling intensively a smaller number of lakes. Results from 2005 indicated that, while the concentrations of some parameters changed throughout the season, the single central sample site seemed to be generally representative of the conditions in each lake at the time. Observed changes between years were likely due to varying climactic conditions between the two years. For example, the summer of 2004 was considerably drier and colder than 2005. The increase in average temperature could have accounted for the significant increase in August chlorophyll *a* concentrations observed in 2005 versus 2004. Total P and total N concentrations was much higher in 2005 than 2004. This may be due to heavy precipitation in June of 2005 that possibly flushed nutrients in from the watershed. Conductivity in 2005 was significantly lower than 2004. While this points to dilution of the water consistent with high precipitation, it does not necessarily support the idea that more ions were flushed into the study lakes increasing nutrient concentrations.

While most of the study lakes were classified as oligotrophic to mesotrophic (Carlson 1977), a number of lakes such as Saxton, Badou, Bernic and Spence Lakes were eutrophic. With the exception of Bernic Lake these lakes were also relatively shallow. It is interesting to note that the majority (95 percent) of the eutrophic lakes have a history of watershed logging, fire or both. Bernic Lake, in addition to having 37 percent of its watershed historically harvested also has an active mine on its shore, which potentially contributed to some of the observed water quality characteristics, for example, high sulphate concentrations. Bernic and Rice Lakes (both lakes with shoreline mining operations) had the highest concentrations of sulphate of all of the study lakes. Concentrations were approximately five times the overall mean. These high concentrations were possibly resulting from the oxidation of sulphide containing minerals mined on the shores of these two lakes. For example, pyrite (iron sulphide) is associated with gold deposits in this region.

Most of the study lakes appeared to be P limited based upon high N to P ratios observed in 2004 and 2005. Decreases in N to P ratios between May and September occurred for unknown reasons. Though these did not correlate with higher production as measured by higher chlorophyll *a,* this would account for the observation of late summer blooms of cyanobacteria (blue green algae).

The presence of an algal toxin (microcystin), albeit at low concentrations, indicated that these toxins occur even in oligotrophic to mesotrophic lakes with limited anthropogenic influence. For unknown reasons, microcystin was detected in 15 lakes in May versus only two lakes in August and three lakes in September. In all cases, microcystin concentrations were below the Canadian drinking water guideline of 1.5 μg/L (Federal Provincial-Territorial Committee on Cyanobacterial Toxins, 1999) and are not likely to be a health risk to human or animal life consuming lake water.

Lower N to P ratio would favour N fixing cyanobacteria that produce microcystin. Field observations of algal blooms (personal observation) and preliminary phytoplankton species identification (Robinson, personal communication) indicate that blue green algae were present in a number of the study lakes in August and September. Some lakes had detectable concentrations of microcystin despite a high N to P ratio.The presence or absence of algal toxins in these lakes seems not to relate to the favorability of the conditions for cyanobacterial growth. In Springer Lake in September and Saxton Lake in August and September, the ratio of N to P decreased to levels which would favour cyanobacteria

(cyanobacteria). Phytoplankton species identification will identify if this occurred. Significant concentrations of chlorophyll *a* were found in August in Saxton Lake (>100μg/L), indicative of an abundance of phytoplankton. September concentrations of chlorophyll in Springer Lake were also somewhat elevated (26 μg/L) but within the range of the other September samples. However, no microcystin was detected in these either Springer Lake or Saxton Lake despite high chlorophyll *a* and phosphorus concentrations. It is important to note however that some species that produce microcystin (i.e. *microcystis*) are not N-fixing but just prefer low N environments.

Algal blooms and the highest concentrations of microcystin were detected in remote lakes not subject to any recent watershed fire or any known anthropogenic perturbation. Blooms of cyanobacteria, and with them elevated concentrations of microcystin, are most commonly associated with anthropogenic disturbance typically in the form of point and non-point P inputs. The data suggest algal blooms were not solely anthropogenic but are natural features of lakes of the region. The highest concentrations of microcystin were found in L87 in May, Lake 59 in August and Lake 60 in September. The watershed of Lake 87 was subject to burning of 58 percent of its watershed 20 years ago, but L59 and L60 were remote lakes in Atikaki Wilderness Park that had no watershed disturbance in the last 50 years. L87 had a very low total P concentration in May (10 μg/L). Total P concentration for Lake 59 in August and Lake 60 in September were below the seasonal averages at 22 μg/L and 23 μg/L, respectively. Field observations indicated a significant algal bloom was in progress in Lake 60 in September.

Algal blooms are a natural feature of the landscape and may not be related to anthropogenic impact. Huyshe (1871) describes travel by canoe from Thunder Bay to Winnipeg via the Winnipeg River system in the summer of 1870. It is probable Lake of the Woods at this time had limited anthropogenic impact to its watershed, yet blooms of phytoplankton occurred.

"… The most noticeable feature of Lake of the Woods is the peculiar green colour of the water, arising from a profuse vegetable growth (*confervae)*. These are a minute, tubular, needle-shaped organism, about half an inch in length, sometimes detached and sometimes clustered together in star-shaped forms: they abound all over the lake, in some place so thickly that the water has the consistence and colour of pea soup. Some of the deep bays receding from the lake, such as Clearwater Bay, are free from this growth, but it extends even a few miles down the Winnipeg River below Rat Portage [now Kenora]. It was impossible to drink the water, or use it for making tea or cooking, until it had been carefully strained" (Huyshe, 1871, Page 162).

Table 30: Lakes with watersheds identified as potential harvest areas in Tembec's Five Year Operating Plan (2004-2009)

Lake ID	Lake Name
5	Lapin Lake
8	Kinsley
9	Springer
16	Eastland
20	Maskwa
34	Beresford Lake
35	Stormy
39	Big Clear water
40	Quesnel
41	Manigotogan
42	Unnamed lake
43	Unnamed lake
45	Spence
51	English
73	Gold
74	Rainy
89	Unnamed lake
90	Unnamed lake
98	Kakaki

5.1.2 Comparison to Historic Data

Mean total P and chlorophyll *a* concentrations measured in the 2004 survey was comparable to those in lakes sampled previously in the study area, specifically the Red Lake district of Ontario and Nopiming Provincial Park (Table 31). The range of chlorophyll concentrations was considerably higher for the 2004 and 2005 surveys than peak concentrations measured for either the Red Lake District or Nopiming Provincial Park.

Table 31: Summary of select historical water quality data in and near the study area.

Source (1.) Government of Manitoba water quality database, (2) Macbeth (2004), (3) Fee et al. (1989), (4) Jones et al. (1996), (5) Ontario Lake Partners (Ontario Ministry of Natural Resources 2005 un published data), (6) City of Winnipeg Water and Waste Department 2004, unpublished data. Note: ND = no data available.

Region	Source	Number of lakes	Sample dates	Total Kjeldahl Nitrogen			Total Nitrogen			Total Phosphorus			Chlorophyll *a*		
				mean mg/L	min	max	mean mg/L	min	max	mean mg/L	Min	max	mean ug/L	low	max
Whiteshell Provincial Park	1	20	1963-1999	0.70	<.2	25.20	ND	ND	ND	0.04	<.001	3.20	10.61	<1.0	910.00
Whiteshell Provincial Park	2	35	July 2002	<.2	<.2	0.40	ND	ND	ND	0.02	0.01	0.08	ND	ND	ND
Nopiming Provincial Park	1	20	1976-1996	0.54	0.23	1.10	ND	ND	ND	0.08	<.02	6.00	5.12	<1.0	25.00
Red Lake District	3	115	Mid-summer 1985	ND	ND	ND	0.53	0.20	1.38	0.02	0.01	0.04	4.59	1.10	17.40
Ponds along Manitoba Highway 304	4	6	1985-1993	0.99	0.50	2.30	ND	ND	ND	0.03	0.50	2.30	10.01	2.10	52.30
Lake of the Woods, Ont.	5	1	Summer 2005	ND	ND	ND	ND	ND	ND	0.02	0.01	0.09	ND	ND	ND
Shoal Lake, Ontario	6	1	2004	0.46	0.31	0.63	ND	ND	ND	0.01	0.01	0.02	5.80	3.00	17.00
2004 Study Lakes		99	Mid-summer 2004	ND	ND	ND	0.72	0.39	1.40	0.02	0.05	0.07	7.20	2.09	5.80

Comparison of lakes sampled in 1985 and 2004

Differences in water quality between 1985 and 2004, based on a set of seven lakes sampled in these two years, were limited. The majority of water chemistry parameters for seven lakes sampled in 1985 (by Fee et al. 1989) and by the present study in 2004 did not differ appreciably between the two years. Total P was higher in concentration in 1985 and was typically low for both studies in all of the lakes with the exception on North and South Eagle lakes in 1985. The reasons for these differences are not clear. However, the watersheds of these two lakes had 32 percent and 15 percent of their watersheds burned within the last 25 years with major fires in 1980 and 1983. Round Lake also experienced watershed fire to 39 percent of its watershed area two years before the 1985 samples were collected. It is possible that these lakes experienced a pulse of P following the fires in 1980 and 1983. Higher nutrient concentrations due to forest fire are supported by 1985 water quality data. Potassium was also elevated in the three "recently" disturbed sites. The fact that concentrations of P were much lower in 2004 samples is consistent with my findings that indicated with respect to lakes with burned watersheds, that beyond 15 years after watershed fire disturbance there was no significant correlation between the proportion of watershed fire and P concentrations. Lake 59, on the other hand, experienced no watershed disturbance in the last 50 years and its total P concentrations were also higher in 1985 versus 2004 samples Paleolimnological reconstruction of the sediment history of these three lakes might indicate if the water chemistry changed after the 1980 and 1983 fires.

5.2 Objective 2

The second objective was to determine the factors influencing lake water quality such as forest type, soil type, proportion of wetlands in a watershed, disturbance type and time since disturbance.

The water chemistry of the study lakes was a function of soil conditions, wetland area, and disturbance history of their respective watersheds. This is not surprising given that terrestrial sources are the foremost contributor of nutrients to lakes (Guildford and Hecky 2000).

5.2.1 Watershed characteristics

Lake water quality was highly affected by the soil type in a watershed. Lakes in areas with poorly developed bedrock soils had low concentrations of N, P, DOC, and alkalinity. This result was expected given granitic bedrock is resistant to erosion and is not expected to contribute substantial nutrients to the study watersheds. Lakes with deep basin and organic soils, on the other hand, were positively correlated with concentrations of total dissolved N, total N and total P and chlorophyll *a*. Deep basin soils were not correlated with high concentrations of DOC or reduced Secchi depth. There was also greater potential for phytoplankton growth as evidenced by increased chlorophyll *a* concentrations. Lakes with organic soils were positively correlated with total dissolved N, total dissolved P, DOC and reduced Secchi depth. Areas with organic soils were typically associated with wetland areas. While organic soils were positively correlated with nutrients, a similar relationship with chlorophyll a was not evident. It is possible higher nutrient concentrations in lakes with organic soils were offset by higher DOC concentrations, which reduced light penetration and restricted growth of algae. Bedrock soils of the region have little organic and mineral content and do not contribute as much N, P, calcium, alkalinity and conductivity from the watershed as do deep basin soils. Bedrock soils are generally thin and nutrient poor whereas deep basin soils are more developed and comparatively nutrient rich.

Phosphorus, N and DOC concentrations were generally higher in lakes with deep basin soils and / or organic soils irrespective of disturbance history. However, there were exceptions. Gold Lake had 93 percent of its watershed in deep basin soil; however, its total P concentration was 20 μg/L, at the low end of the observed range. Happy Lake, Lake 82, Lake 83, and Okimaw Lake had 31 percent, 40 percent and 75 percent of their watersheds in organic soil. Though lakes with organic soils generally had higher than average concentrations of total dissolved P, soil conditions alone were not responsible for the water quality observed.

The percentage of wetlands in the lake watershed (Muskeg, Treed Muskeg, Beaver Flood and Willow Alder from the Forest Resource Inventory) had a significant influence on the chemical and physical characteristics of the water body. The percentage of wetlands in the watershed was positively correlated with DOC ($r^2 = 0.41$). Wetlands were also associated with higher concentrations of total dissolved N, and decreased Secchi depth. An increasing proportion of wetlands in the catchment was also associated decreased concentrations of sulphate and dissolved P. A high percentage of wetlands was not associated with a corresponding high concentration of chlorophyll *a* in 2004. It is likely high DOC concentrations limited light penetration into the water column restricting phytoplankton growth.. DOC in lake water typically occurs due to the leaching of soil and plant material. DOC concentration may be controlled by a primary production of plant matter and decomposition rates (Thurman 1985).

Lake water quality tended to correlate with the forest type in the surrounding watershed in that individual tree species have distinct nutritional requirements related to specific soil which, in turn, can contribute certain chemicals to lake water. Total P concentration and alkalinity was inversely related to the percentage of jack pine (*Pinus banksiana*) in a watershed. Dissolved N, total N, calcium, conductivity were also negatively associated the proportion of jack pine. Jack pine typically grows on shallow soils and may grow in crevasses on bare rock. Therefore, these results were expected. Black spruce percentage did not appear to be strongly related to any of the chemical or physical characteristics of the sampled lakes. This result was not surprising as Black Spruce is a generalist tree species that can grow on shallow, upland soils as well as deep organic soils. Suspended N, suspended and dissolved P was positively correlated with the proportion of hardwood tree species, such as trembling aspen and white birch in a watershed, DOC on the other hand was negatively correlated with hardwood abundance. Chlorophyll *a* was slightly elevated in hardwood-dominated watersheds though this was not statistically significant.

5.2.2 Disturbance History

The effects of forest harvest and forest fires on water quality appear to be different from each other. Part of the discrepancy could be due to inclusion of fire-affected watersheds within Atikaki Park where no watershed harvesting has occurred and nutrient concentrations were generally lower than in more southern lakes.

Following watershed fire, it is expected that nutrient concentrations would be more biologically available, to trigger for example, increased algal biomass. Nutrients in lakes with watershed fire were in more bioavailabile forms (total dissolved N and dissolved P) than lakes with watershed harvesting. Concerning total concentrations of N, lakes with burned watersheds were not significantly different from reference lakes. Total P concentrations in burned lakes were significantly different from reference lakes and lakes with watershed harvesting.

Lakes with watershed harvesting and watershed fire within the last five years were not associated with increased concentrations of any of the water quality parameters. The fact that recent fires were restricted to the north of the study area where soils are almost exclusively bedrock-dominated may account for some of these observations. Furthermore, recent harvests have removed a small proportion of the watershed. Carignan et al. (2000) suggested that major changes to water quality may not occur unless greater than 30 percent of a watershed is disturbed. Concerning lakes grouped by disturbance type, total N concentrations were similar between lakes with harvested (average disturbance 39 percent) and burned watersheds (63 percent). However, total P was significantly higher in lakes with watershed harvesting and elevated concentrations occurred over a longer period. For example, the cumulative proportion of a watershed burned within the last 35 years was not significantly correlated with any water quality variable whereas forest harvesting was positively correlated with concentration of TDN, TP, calcium, alkalinity, conductivity, and chlorophyll *a*. The cumulative proportion of a watershed burned within the last 15 years was significantly correlated with elevated concentrations of dissolved and total P. This appears to indicate that the effect of watershed fire on P concentrations, is short-lived (~15 years). Bayley and Shindler (1991) suggested that elevated losses of base cations and elevated total P concentrations in lakes affected by forest fire could last between five to nine years following wildfire disturbance. The data support this conclusion.

The cumulative proportion of forest harvesting within the last 15, 35 and 50 years was positively correlated with total dissolved N, total N and DOC and total P concentrations. The proportion of the watershed harvested also strongly correlated with increased calcium, alkalinity, conductivity and chlorophyll *a* concentrations. This indicates that the effects of forest harvesting are potentially long term (greater than 15 years). This agrees with the conclusions reached in Quebec (Carigan et al. 2000, Pinel-Alloul 2002) and in Finland (Ahtiainen 1993, Turkia et al 1998).

The degree to which forest harvesting affects water quality is likely variable with the soil type in the watershed. For example, whereas Prepas et al. (2001) found significant increases in total P and chlorophyll *a* following harvest disturbance to an average of 15 percent watershed area in the nutrient rich boreal plain of Alberta, Carignan et al. (2000) found that it took harvest disturbance to 30 percent watershed area to produce similar effects in lakes of the rocky boreal shield of Quebec. This would indicate that lakes dominated by rich, well developed soils should naturally have higher nutrient concentrations. With respect to watersheds with deep basin soils and or organic soils in this study, this does not always hold true. For example, Farrington Lake had the second highest concentration of P yet was dominated by bedrock, had a low watershed to lake area ratio (12) but had a high proportion of the watershed disturbed (45 percent within the last 35 years). Conversely, Gold Lake and Lake 96 were dominated by deep basin soils (~90 percent) yet had moderate to low concentrations of total P of 20 μg/L and 11 μg/L respectively. On the other hand, Saxton Lake, which had the highest concentration of nutrients, had a high proportion of its watershed disturbed by forest harvesting (49 percent since 1978), a high watershed to lake area ratio (56) and a high proportion of more nutrient rich deep basin soils (43 percent). It is possible that nutrient concentrations have always been high in Saxton Lake though a significant disturbance history and nutrient rich soil type likely influenced its water quality. Saxton Lake had a large proportion of the watershed harvested, deep basin soil and experienced site preparation in the form of disk trenching.

Forest fire and forest harvesting affect water quality in different ways. Though concentrations for some parameters (e.g., TN, TP and DOC) were elevated in burned and harvested systems, lakes with watershed fire on average had lower concentrations despite an overall higher proportion of disturbance (59 percent for forest fire versus 39 percent for forest harvesting). If forest fire and forest harvesting affect lakes the same way, the effects from both would be the same and proportional to the area disturbed. During a fire, the forest biomass is mineralized whereas tree needles, bark, and branches are left on a harvested site as a nutrient and seed source to enhance forest regeneration. This new input of litter on the forest floor is a possible long-term source of dissolved organic matter and nutrients to the watershed. The soil remains at a harvested site whereas, the entire soil and duff layer may be burned away, depending on the intensity and frequency of fire. This would account for the finding that N and P were predominantly in dissolved form in lakes with burned watersheds while they were in suspended forms in harvested watersheds. Some dissolved forms of N and P are more biologically available and may enhance the growth of algae more immediately. Field observations indicated that mid and late summer phytoplankton blooms were evident in a number of historically burned systems.

The longevity of nutrient export from a watershed and thus the total load of nutrients to a lake can be influenced by the time it takes for the forest to re-grow and for evapotranspiration to stabilize. However, internal recycling may be a considerable source of nutrients for many years to come. During the summer, thermal stratification may prevent re-suspension of nutrients from the sediments while N and P would be available throughout the year in shallow poorly stratified lakes. However in deeply stratified lakes where oxygen is depleted in the hypolimnion over the summer, inorganic N and P may be released from the sediments and then mixed into the upper waters during fall turnover or in the summer when stratification is broken by strong winds. It was hypothesized that forest harvesting and forest fire would increase nutrient and sediment transport to lakes, thereby increasing concentrations of N and P in lake water. Unfortunately, without pre-disturbance data, it was not able to determine how much the water chemistry of the lakes changed as result of watershed disturbance. However, total P and total N were 1.7 and 1.3 times greater in harvested lakes versus reference lakes, respectively. Chlorophyll *a* was 2.2 times higher in lakes with watershed harvesting than reference lakes, and two times higher than lakes with burned watersheds. Lakes with burned watersheds had N concentrations similar to reference lakes though P concentrations were 1.3 times higher with burned watersheds. With respect to harvested lakes, calcium, magnesium, sodium, potassium and conductivity were 2 to 2.6 times higher than reference lakes, respectively, while alkalinity was 3.2 times higher than reference lakes. Similarly, concentrations of calcium, magnesium, sodium, potassium and conductivity in harvested lakes were between 1.7 to 2.1 times higher than lakes with burned watersheds. The data therefore support the hypothesis that lakes with forest harvesting and forest fire have higher concentrations of N and P. Furthermore, the magnitude of these differing concentrations of nutrients were expected to be directly proportional to the percentage of the watershed disturbed. A number of lakes, for example, L63, Lake 62 and Manning Lake were subject to repeat fire disturbance over 100 percent of the watershed area within the last 50 years. However, with the exception of Manning Lake, not all of these lakes had higher concentrations of nutrients. Manning Lake had a total P concentration (33 μg/L), approximately two to three times higher than L62 and L63, respectively, and two times the average for reference lakes. This did not translate into high chlorophyll *a* concentration. The reasons for this are unclear though the majority of the P was in suspended form and it is possible that it was not available for biological uptake. The year 2004 had an exceptionally cool summer; May to August was on average approximately 4°C colder than normal. It is possible it was not warm enough to trigger large algal blooms. Average temperatures in 2005 were approximately 1°C warmer than normal and extensive phytoplankton blooms were observed in August and September in a number of the study lakes. Manning Lake was excluded from sampling in July and August of 2005 due to its small size.

Watersheds with a high proportion of watershed harvesting generally had different water quality from reference lakes. Saxton, Farrington, and Little Beaver Lakes had a high proportion of their watersheds harvested and displayed the most eutrophic water quality. However, this was not always the case. Blue Lake had 61 percent of its watershed harvested within the last 50 years yet its total P (17 μg/L) was considerably lower than the mean for the harvested lakes (25 μg/L). However, DOC and calcium concentrations were elevated in Blue Lake. Rush Lake had 66 percent of its watershed harvested yet its water quality was not appreciably differently from the other harvested lakes. Harvesting operations in the Rush and Blue Lake watersheds were completed in 1975. It is possible that if these lakes were historically impacted by logging operations, water quality had recovered partially. Birse Lake had a high proportion of watershed harvesting (36 percent) yet had low concentrations of P, calcium, and DOC. Birse Lake is a deep stratified lake where watershed harvesting of the watershed occurred prior to 1980, it has a bedrock-dominated watershed and has a low watershed to lake area ratio (4.6) so it is not expected to be sensitive to drainage basin disturbance. Water quality of Birse Lake was consistent with an oligotrophic system although alkalinity was elevated (608 μ eq of calcium carbonate) and nitrate was elevated at 20 μg/L. Lake 43 on the other hand had only 17 percent of its watershed logged yet had significantly elevated concentrations of DOC. Lake 43 is a shallow wetland-dominated lake, which probably explains its high DOC concentrations.

Lakes with disturbance older 15 years and older had higher concentrations of major nutrients than lakes with recent disturbance. Contrary to my hypothesis that lakes with recent forest disturbance would have higher concentrations of nutrients relative to reference systems and lakes with historically disturbed watersheds, it was lakes with older harvests (e.g., Saxton, and Farrington Lakes) that demonstrated the highest concentration of nutrients. Although lakes with a high proportion of fire disturbance in the last 15 years were positively correlated with total dissolved P, unlike harvested watersheds, there was no correlation with the cumulative proportion of the watershed burned within the last 35 years. The data indicate that if watershed disturbance is associated with increased eutrophy of the lake water, the effects of forest harvesting occur on a longer time scale than those associated with forest fire. Forest harvesting within the last 50 years was correlated with higher concentrations of DOC. Typically, older timber harvests targeted black spruce dominated stands for the paper milling process (Kotak et al. 2005). Black spruce prefers wetland habitat that naturally export higher concentrations of DOC, TN and TP..

The proportion of linear features (e.g., roads, trails, and powerlines) in a watershed did not appear to be related to the water quality of the study lakes. It is possible that possible effects resulting from linear features were masked by the overall variability of the study lakes. There is considerable debate surrounding the construction of an all-weather road on the east side of Lake Winnipeg to service remote communities and/or the development of hydroelectric transmission lines for export of electricity. A companion stream monitoring project (Kotak et al. 2005) found significant correlations between road density and stream water concentrations of sulphate, total dissolved P total N and DOC. However, these correlations were attributed to winter roads as opposed to all weather roads or power-lines. Winter roads are typically built over wetland areas. Given this, the observed correlations were likely attributable to wetland soil types rather than any road effect. My study found no such correlations. Although all-weather road density was not related to lake water quality in the study lakes, there may be other important impacts of linear features, on wildlife migration, the spread of forest pests, degradation of aesthetics, and providing people access to sensitive areas.

5.3 Objective 3

The third objective of this study was to identify watersheds sensitive to harvest disturbance as well as candidate lakes for long term monitoring.

5.3.1 Lakes sensitive to watershed disturbance

The data show that a sensitive watershed had a high proportion of the watershed disturbed, a high drainage ratio (watershed to lake area ratio), a proportion of the watershed in deep basin or organic soils, and a high proportion of wetlands. In watersheds with steeply sloped basins, topography may be a significant factor on a lake-to-lake basis because steeply sloped watersheds may be subject to greater erosion processes. Topography is not likely an issue for watersheds on the east side of Lake Winnipeg. Based on the analysis of the five year operating plan (2004 to 2009) and soil conditions in the planned harvest area, the following lakes are most susceptible to watershed disturbance: Spence Lake, Big Clear Water Lake, English Lake, Gold, L74, L49, L48, Kakaki, L96, Okimaw, Happy Lake, Little Beaver Lake, North Eagle, South Eagle and Saxton. These lakes have a larger proportion of nutrient-rich, deep basin soils and are in the planned harvest area identified by Tembec. When soils and harvest history information from Ontario becomes available, this list can be expanded to include lakes with origins in Ontario.

Lakes with a high drainage ratio (a high watershed to lake area ratio) experience more rapid flushing of nutrients from the watershed based on a greater volume of surface area drained relative to the lake area/ volume. Lake 74, Kakaki, Spence, English, Lake 48 and Lake 49 have higher than average (of all study lakes) drainage ratios and are likely more sensitive to watershed disturbance. Lake 48 and Lake 49, despite having a high drainage ratio and a higher proportion of deep basin soils, are distant from the planned operating area and are not likely to be harvested though these lakes may be sensitive to fire disturbance. Gold Lake, Lake 96 and Big Clear Water Lake have lower drainage ratios. Big Clear Water Lake is not likely as sensitive to watershed disturbance given it is large with a long residence time (low watershed to lake area ratio). Schindler et al. (1980) suggest that deforestation is not likely to have a major impact on water quality unless the mean residence time is short relative to the time needed for revegetation. Spence Lake has naturally elevated concentrations of dissolved N, total P, DOC, and chlorophyll *a*; in addition, Spence Lake has a high drainage ratio, a higher proportion of deep basin soils and a larger proportion of wetlands in the catchment, it can therefore be considered relatively sensitive to watershed disturbance. It is important to note that although nutrient export may increase with watershed disturbance in lakes with organic soils or a high proportion of wetland area, excessive blooms of algae may not readily occur because high DOC concentrations limit light penetration.

Lakes with a high proportion of wetlands are expected to be more sensitive to watershed disturbance than basins with less wetland area. Watersheds with a a greater proportion of wetlands had nutrient concentrations in lake water than lakes from upland areas. Wetland basins are expected to export more P and N when burned than forested upland watersheds (Bayley et al. 1992). Okimaw, Kakaki and Lake 49 had the highest proportion of wetlands in their drainage basins at 43, 42 and 38 percent, respectively. The proportion of wetlands in Gold and English and Lake 74 were also relatively high at 33 and 30 percent. It is expected that these lakes would be sensitive to watershed disturbance. However, Saxton Lake and Little Beaver Lake had a low percentage of wetlands (15 and 17 percent) yet seemed to be highly influenced by watershed disturbance. It seems disturbance history may have an overriding influence on water quality though soil and wetland conditions contribute to the observed conditions in disturbed sites. Best management practices in wetland areas such as winter harvesting may help mitigate possible effects of logging trees on wetland soils.

5.3.2 Candidate Lakes for Long Term Monitoring

Several of the study lakes would be well suited for use in a long-term water quality monitoring program, based on selection criteria of Fee et al. (1989). Candidate lakes should be easily accessible such that monitoring can occur over a long period at a moderate cost. The study region should contain a large number of lakes of various sizes, sufficiently remote that anthropogenic influences are minimal. The region should be geologically and meteorologically uniform. Lakes should also be large enough that they are accessible by most aircraft under all feasible wind conditions. By these criteria, most lakes within Atikaki Wilderness Park are ideal. The region is sufficiently accessible by air, yet the region is protected from most forms of anthropogenic activity and the geology and meteorology is generally uniform. Lakes sampled in this study which meet these criteria include Lake 59, L60, Round Lake, Sasaginnigak Lake, Aikins, Dogskin, and Lake 81. When examining the effects of watershed disturbance, whether natural or anthropogenic, the effects to water quality may be masked by influxes from tributaries on large watersheds. For example, Aikins, Dogskin and Sasaginnigak Lakes are all on large watersheds originating in Ontario. While these may be suitable lakes for long term monitoring (i.e. accessible, removed from human activity, large, with representative geology), it would be difficult to identify disturbance in the watershed of these lakes affecting their water chemistry. South of Atikaki Wilderness Park, several lakes may be suitable for long term monitoring; for example, Gordon Lake, Happy Lake, and Spence Lake. In addition, any of the sensitive lakes identified earlier would be good candidates for long term monitoring. Cottage associations may be interested in volunteer water quality monitoring programs; these should be encouraged. Such programs would be cost effective, and would engage the public as informed stakeholders in lake stewardship. Ideally, monitoring should also include lakes with historical disturbance. For example, Saxton Lake was unique with respect to its water quality. Full recovery of a lake may take over 75 years, long term monitoring of Saxton Lake would help to indicate this. Paleolimniological reconstruction of the sediment history can be used to identify if Saxton Lake was always eutrophic or whether this has changed through the limnological record.

5.4 Objective 4

5.4.1 Implications for Watershed Harvesting

The fourth objective was to use water quality survey data and disturbance history information to determine if there is any rationale for restricting harvesting levels to a percentage of a watershed. Although it is impossible to mitigate all the effects of forest management operations, current management objectives aim to have impacts that are within the range of natural disturbance by wildfire and other factors. Currently, Tembec voluntarily restricts recent watershed disturbance to below 30 percent of the gross productive forest land in a watershed. Recent watershed disturbance is defined as that caused by fire or harvest within the last seven years and corresponds with forest regeneration surveys to determine stocking rates of trees in harvested areas. The timeframe of seven years is arbitrary and has no scientific basis to the recovery of evapotranspration and the subsequent reduction in export rates of nutrients from a watershed.

Elsewhere in Manitoba, Louisiana Pacific Canada (Swan Valley operation) has a 30 percent recent watershed harvesting restriction as part of their Manitoba Environment Act License. Recent harvesting is defined as that occurring within the last five years for hardwood species and 15 years for softwood species and excludes examination of forest fire disturbance. Similar to Tembec, the five-year period used by Louisiana Pacific Canada corresponds to the "free to grow stage" of regeneration surveys and has no scientific basis with respect to hydrology or the maintenance of water quality. Louisiana Pacific, Tembec and other forestry companies should engage in a parallel water quality-monitoring program and companion watershed harvesting study in their forest management leases to determine if there is a scientifically justifiable rationale for a 30 percent harvest level and if the period of five or seven years has any basis in terms of the time needed for recovery of evapotranspiration and subsequent watershed nutrient export.

Furthermore, the scale at which Tembec manages their watersheds is very large and is based upon river watersheds as opposed to lakes. The average size of Tembec's watersheds ranges from 1,700 to 79,000 hectares with a mean of 27,000 hectares. Louisiana Pacific manages their watersheds on a sub drainage basin level. While watersheds may correspond well to administrative boundaries the use of watersheds of this scale makes prediction of the effects of watershed harvesting difficult. It is unlikely that any differences in water quality attributable to watershed disturbance would be noticeable when using a mean watershed size of 27,000 hectares. It is possible that voluntary (Tembec) or mandatory (Louisiana Pacific) watershed harvesting restrictions of 30 percent nevertheless permit a considerable opportunity for greater than 30 percent harvesting to occur on a smaller watershed scale. While the overall proportion of a large watershed disturbed may be low, disturbance levels may be considerably higher on the individual stream or lake watershed level. Tembec and Louisiana Pacific should consider breaking watersheds into smaller management units for the protection of water quality. While it may not be practical to manage watersheds on the scale used in this study, Tembec should consider breaking up some of its larger watersheds, the size of which should not exceed 10,000 hectares (Rothwell 1997, Kotak et al 2005)).

Although Tembec and Louisiana Pacific apply a limit of 30 percent disturbance between five and seven years, my data suggest that forest harvesting does affect water quality for a much longer time period. This appears particularly true with watersheds with nutrient-rich soils. In these cases, a 30 percent watershed harvesting restriction may be a good general rule. On nutrient rich sites and sites subject to erosion, a lower proportion of watershed harvesting may be appropriate. For example, in the comparatively P-rich Boreal Plain of Alberta, Prepas et al. (2001) found that significant changes to total P, DOC and chlorophyll *a* occurred when an average of only 15 percent of the watershed area of eleven lakes was harvested.

Nutrient export from watersheds is linked to re-vegetation of a site and subsequent resumption of evapotranspiration. Evapotranspiration and the subsequent return to pre-disturbance water quality conditions may be rapid (three to six years) in the hardwood dominated Hubbard Brook Experimental Forest of New Hampshire (Martin et al. 2000). However, it may take between 30 years or longer in a coniferous or Pine dominated forest (Swanson and Hillman 1977; Rothwell 1997). A study of recovery of evapotranspiration and nutrient export would help determine whether a seven-year period is appropriate in Manitoba.

The data suggest that unrestricted watershed harvesting of between 37 to 67 percent has influenced lake water quality in the region. Thus, there are grounds for managing watershed harvesting levels; this percentage should be evaluated on a watershed-to-watershed basis. Differences in watershed soil conditions (nutrient rich soils versus bedrock soils), and the proportion of wetland areas and relief (steep slopes versus flatland) are factors that may make some watersheds prone to disturbance.

Currently, the government of Manitoba is conducting a timber supply analysis and is soliciting proposals for construction of an oriented strand board (OSB) plant. If such a plant is constructed, it is probable that a considerable amount of its timber supply would come from the study area, increasing the overall amount of forest harvesting. Currently, the majority of hardwood trees (trembling aspen, white birch) are left unharvested by Tembec, as they are not suited to their paper making process but such tree species can be used for making OSB. These species typically grow on better developed, nutrient-rich soils than the softwoods. Harvesting of hardwood species may release more nutrients than harvesting on bedrock soils. Water quality in catchments with hardwood harvesting may be more sensitive to harvesting of softwoods growing on nutrient poor bedrock soils.

Chapter 6: Recommendations

6.1 Recommendation for Future Research

A long-term water quality monitoring program to be undertaken in lakes with watershed disturbance. It might take years after watershed disturbance for noticeable effects to be observed. The fact that areas with recent forest harvesting have little differences observed from reference sites indicate that a long-term monitoring program not only in disturbed systems but also in remote reference systems is needed to address some of these data gaps. Ideally, monitoring should start before actual timber harvesting operations commence, and continue throughout the harvest and many years post-harvest. The monitoring program should measure, as a minimum, nutrient chemistry, dissolved oxygen profiles, water temperature, and Secchi depth. Additional analyses of phytoplankton, zooplankton and fish species composition, and trace metal analysis would be desirable.

A controlled manipulative experiment should be initiated to examine the effects of watershed harvesting or fire on lake water quality before, during, and after disturbance. Though speculation is easy, it is impossible to conclude that the present status of water quality in the most eutrophic lakes is result of a high degree of disturbance without pre-disturbance baseline water quality. For example, these lakes could have always been fertile due to soil and forest composition in these watersheds. A controlled manipulative experiment would determine exactly how disturbance influences water quality in this region. For example, a watershed harvesting experiment should be conducted within the Manitoba Model Forest Area (roughly the Tembec Forest Management License Area). A series of paired harvested and un-harvested watersheds with a gradient of watershed harvesting, for example 15 percent, 30 percent and 50 percent , would be the ideal method for this. This study should measure include bi-weekly to monthly analysis of nutrient chemistry, dissolved oxygen profiles, water temperature, Secchi depth, and light extinction. Additional analyses of phytoplankton, zooplankton and fish species composition and trace metal analysis would be desirable. This study should include at least one year to two years of baseline pre-disturbance, monitoring during catchment manipulation and continue as long as possible (at least 10 years) after disturbance.

A paleolimnological investigation of past water quality conditions in the region through analysis of sediment cores should be undertaken. Paleolimnological analysis is a powerful tool to gain insights into the past environmental conditions of the study lakes and provide predictions as to the conditions in lakes affected by natural or anthropogenic disturbance. Paleolimnological analysis should be conducted on selected lakes to identify if water quality has changed over time and if any observed changes correlate with historical activities in the respective watersheds. Analysis of the diatom species assemblage through the sediment could determine past nutrient conditions in lakes by inferring species abundance based on the nutritional requirements of each species. Paleolimnology could be used to reconstruct the post glacial fire history in the lakes. In addition, using radio isotope dating techniques, sediment profiles from the last century could be examined for changes in organic C, deposition rates and chemistry consistent with disturbance history. Several lakes would be suitable for sediment core analysis including; Aikins, Round Lake, Terminal Lake, Little Beaver Lake, Bernic Lake, Happy Lake, L87, English Lake, Glen Lake and Wallace Lake. These lakes were observed to thermally stratify, were generally deep enough to prevent perturbation of the sediment, and come from a variety of reference, historically harvested and burned watersheds.

Ground water movement should be researched. This study was unable to address the hydrologic influences and ground water movement in the study watersheds. I assumed that water movement and consequently nutrient input into the study lakes occurred as a result of overland flow following a topographic gradient. Although presumed water will flow from high elevation to low, the movement of ground water may follow a considerably different path. A network of pizometer nests, climate and hydrologic monitoring infrastructure in a subset of Manitoba Model Forest area would achieve a better understanding of water movement in the study watersheds.

Improved knowledge of soil conditions in the regions watersheds is required. There was little quantitative information on soil types and soil nutrient concentrations in the study watersheds. Inferred conclusions were based on the premise that more developed deeper soils were more nutrient rich. A better understanding of soil conditions, through the sampling and chemical analysis of nutrient composition in terrestrial soils would lead to a better understanding of export rates of nutrients from the watersheds.

Sample collection for mercury analysis and other trace metals should be initiated. Recent research suggests mercury concentration may increase due to forest management activities and fire (Garcia and Carignan 2000). If forest harvesting increases watershed export of mercury this potentially could lead to higher mercury concentrations in fish and consequently have implications for higher order consumers. Sampling for mercury in water, zooplankton and fish in lakes disturbed by fire, forest harvesting, mining and reference sites would help answer this important question. A study of mercury should include an examination of photodegradation particularly as it relates to DOC levels and light transmission.

Traditional and local ecological knowledge should be included in future research. This study had no public involvement. Cottage owners, trappers, hunters and anglers may have considerable knowledge regarding changes to water quality in their local waters. Including their knowledge in future, research through interviews, surveys or focus groups may shed considerable light onto water quality concerns and perceptions of changes in the region.

6.2 Recommendations for Resource Management

The watershed scale at which Tembec currently manages should be broken up into smaller management units, the size of which should be no larger than 100 km^2 (Rothwell 1997). For reasons stated earlier, it is unlikely that management of watersheds at the current scale has any relevance to the protection of water quality on the individual lake or stream level. Watershed disturbance is predicted to affect smaller watersheds more than larger ones (Hetherington 1987, Rothwell 1997).

An enhanced data sharing agreement between Ontario and Manitoba should be implemented. The lack of an effective data sharing agreement between Manitoba and Ontario necessitated the exclusion of considerable data from the analysis of the watershed features on water quality. Databases for the Ontario forest resource inventory, fire and harvest disturbance history would have been useful. Water quality issues are often trans-boundary in nature. Though the results of this study will be of interest to agencies in Ontario and Manitoba, the lack of effective and timely co-operation in data sharing between the two provinces reduced the efficacy of this study. An enhanced data sharing agreement for scientific use would be desirable.

The forest resource inventory for Atakaki Park should be updated.

The forest resource inventory for Atakaki Provincial Wilderness Park has not been updated since 1983. The park is protected from resource extraction activities and such activities are the primary purpose behind the forest resource inventory. However, considerable scientific knowledge can be gained from an update of the forest resource inventory. Very little is known about landforms on the East Side of Lake Winnipeg. Updating the forest resource inventory would permit a long-term evaluation of any changes to the landscape.

Soils and wetlands of the region should be mapped at a finer scale. The available soils data for the region is mapped at a scale of 1:1,000,000. Although this is suitable for an initial comparison of the region, mapping at this scale may not accurately reflect soil conditions on the lake watershed scale. More detailed mapping of soil and wetland data would provide for a better understanding of how soil and wetland types influence the water quality in the region.

Collection of water quality data should be undertaken in pre- and post-harvest assessments. Although this study has considerably increased knowledge of water quality in lakes on the east side of Lake Winnipeg, it was impossible to sample every lake. Including water quality monitoring as a pre and post harvest assessments would increase this knowledge and provide opportunity to survey water quality pre- and post-harvest.

Public participation should be encouraged in future water quality monitoring programs.

There was considerable interest in the water quality of the region amongst campers, anglers, cottage owners, trappers and municipal officials expressed through informal conversation during this research. Typically, concerns revolved around human health issues and the suitability of lake water for drinking. There is considerable opportunity for a volunteer water quality-monitoring program in lakes with cottage subdivisions and remote wilderness lakes. A number of cottages also exist on remote lakes. A volunteer sampling program arranged through local cottage, hunters and trappers organizations would allow for valuable data collection at minimal cost. The monitoring program could possibly be modeled after the Ontario Lake Partners Program. The aim of the Ontario lake partners program "…is to create a valuable, long term database to evaluate the nutrient status of Ontario's inland lakes" (Ontario Ministry of the Environment 2004). Volunteer monitors collect water samples for total phosphorus one to four times during the open water season and monthly Secchi depth readings. Samples are delivered to the analytical lab in postage paid envelopes. A volunteer monitoring program would provide an opportunity to engage the public in the development of a long-term dataset to monitor water quality changes in Manitoba lakes.

Public education and monitoring of cottage waste water should be undertaken by the Province. As the population ages and formerly seasonal cottages become year-round homes, there is increased opportunity for cultural eutrophication of lakes of Nopiming Provincial Park and elsewhere. Although most cottages are required to have wastewater-holding tanks, a number of cottages have only primitive latrines. There is also considerable opportunity for grey water run off and as more people pursue the conveniences of urban living at their cottages, the opportunity for nutrient-rich runoff increases. For example, automatic dishwasher detergent may contain considerable concentrations of P. An education program aimed at cottage owners and inspection of wastewater holding facilities would help alleviate these concerns.

6.3 Recommendations for the Public

Cottage owners should initiate best practices for shoreline living. Regular users of the regions waters have first hand knowledge of changes to water quality over time. Concerned public should familiarize themselves with water quality issues and implement the best practices developed by others for the protection of water quality. The "Living by Water Project" provides excellent advice. For example, an improper or malfunctioning sewage system can significantly degrade lake water quality. Regular maintenance and inspection of a sewage system is essential for the maintenance of water quality particularly in a dense cottage community. Lawn fertilizers can also contribute considerable amounts of N and P to receiving waters particularly on bedrock dominated soil that has limited assimilation capacity for excess nutrients. Lawn fertilizers therefore should not be used.

The public should be encouraged to monitor changes in their lake via the initiation of volunteer water quality monitoring programs. Collecting Secchi depths routinely and taking photographs of unusual events (e.g., algae blooms) can provide documentation of water quality changes. The public should talk to their government officials and scientists about water quality concerns. Such dialog may provide the seed for valuable research.

Summary

Water quality in remote lakes on the east side of Lake Winnipeg is largely unknown. This study was the first characterization of the baseline conditions in these lakes. Water quality of the epilimnion of 99 boreal shield lakes was sampled by floatplane in 2004 (July) and 2005 (May, August, and September). Most of the study lakes were relatively shallow with an average depth of approximately five meters. A number of deeper lakes in the study area had maximum depths greater than 20 meters. Most of the study lakes were classified as oligotrophic to mesotrophic, but a few were eutrophic. The presence of microcystin in remote lakes with no history of watershed fire of anthropogenic perturbation indicated that algal toxins occur even in remote oligotrophic to mesotrophic lakes with limited anthropogenic influence.

Water quality in this region was affected by characteristics of the watershed such as soil type, the proportion of wetlands in the watershed, and forest type. Lakes in areas with poorly developed bedrock soils had low concentrations of N, P, DOC, and alkalinity while lakes with deep basin and organic soils were positively correlated with concentrations of TDN, TN, TDP, DOC , TN and TP, chlorophyll *a*. Reduced Secchi depth was positively correlated with Organic soils. Concentrations of DOC, TDN, sulphate, TDP, and decreasing Secchi depth in lake water were positively correlated with the proportion of wetlands in a watershed. Concentrations of suspended N, suspended and dissolved P were associated with the proportion of hardwood tree species, such as trembling aspen and white birch in a watershed, while concentrations of most chemical constituents was lower in watersheds dominated by jack pine forest.

Watershed disturbance such as forest fire and forest harvesting had a marked

influence on water quality. Forest harvesting disturbance and to a lesser extent fire disturbance was associated with the most eutrophic lakes. The greatest differences compared to reference sites occurred when a large proportion of a watershed had been disturbed. Concentrations of most water quality parameters were significantly higher in lakes with harvested and burned watersheds compared to reference lakes. Lakes with watershed harvesting and watershed fire within the last five years were not associated with increased concentrations of any of the water quality parameters. However, the cumulative proportion of a watershed burned within the last 15 years was correlated with elevated concentrations of TDP, TP while forest harvesting within the last 15, 35 and 50 years was correlated with TP, TDN, TN, DOC, Ca, alkalinity, conductivity, and chlorophyll *a*. The data demonstrate that the effects of forest harvesting on water quality may occur longer than watershed fire. A sensitive watershed had a high proportion of the watershed disturbed, a high drainage ratio (watershed to lake area ratio), a high proportion of the watershed in deep basin or organic soils, and a high proportion of wetlands.

Currently, Tembec Inc. (in whose forest licence area this study was done) voluntarily restricts watershed disturbance within seven years to below 30 percent of the gross productive forest land in a watershed. The timeframe of seven years is arbitrary and has no scientific basis. Furthermore, the scale at which Tembec manages their watersheds is very large and should be divided into smaller management units. A long-term water quality monitoring program and a controlled watershed harvesting experiment should also be initiated to determine the effects of watershed harvesting or fire on lake water quality, before, during, and after disturbance.

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Appendices:

Using Small Aircraft for Limnology Research: observations and recommendations

Aircraft without a doubt has dramatically affected Canada's North, opening it to economic activities, allowing economic development and settlement in a region that ordinarily would be inaccessible without an arduous journey over water. A floatplane is almost an ideal platform for sampling water quality in remote lakes. Aside a float equipped helicopter or lengthy portage by canoe, it is the only way to sample a large number of remote lakes. Among the advantages of using floatplanes in water quality survey work is it opens up otherwise inaccessible areas for investigation. The relatively high speed of travel allows many lakes to be sampled each day transversing large areas of geography. The relatively stable platform of the floats is comfortable for sampling under most wave conditions encountered in small lakes. Though costs may seem high at $200 per hour, this is usually charged only on aircraft engine running time. However, some companies will charge a minimum number of hours per day.

The challenging geography of the north presents many factors that should be taken into account when conducting work of this nature. Given that many of the study lakes had never been landed on before, extra precautions were needed. Rock, submerged trees and reefs all present a hazard to a landing and taking off aircraft for obvious reasons. Weed beds encountered in shallow lakes can clog water rudders. Survival equipment and a device to communicate to the outside world in the event of an emergency should be carried at all times. Satellite phones can be easily rented and while expensive, the overall cost compared to aircraft operations is small. In the event of an emergency or preventing a costly search if your aircraft is overdue because of waiting out weather, mechanical breakdown or lack of remaining daylight, this cost becomes negligible. When operating in a remote area leaving a flight itinerary with a responsible person is essential. Include a photocopy of a map of area of the area you will be working in, including the names/ locations of the lakes and the order in which you plan to visit them. Ensure that the responsible person is one who will notify the proper authorities should you become overdue. We have been two hours late of our intended arrival time and notified the "responsible person" of our arrival only to get their answering machine!

Many of the lakes sampled in 2004/2005 were small shallow lakes, which necessitated specialized take off techniques (e.g. turning take offs and step taxi turns). Given the small nature of many of these lakes, particular attention must be paid to the crosswind component on take off and landing which is usually not as much a factor when flying floatplanes on larger lakes. A thorough knowledge of ones aircraft performance is needed before attempting to land in many of these smaller lakes. Keep in mind that it takes at least twice the landing amount to take off. On the part of researcher, chosen lake size should reflect the capabilities of an average aircraft. In 2005, an accident necessitated the switch from a Piper Super Cub to a Cessna 172. Given the limited takeoff performance capabilities of the second aircraft compared to the first, a number of lakes had to be excluded from the sampling program. Despite eliminating a number of lakes, a number of takeoffs required two attempts, while many challenged the capabilities of the aircraft and pilot alike.

Careful attention must be paid to gross weight of the aircraft. Cargo limitations on a small aircraft make transportation of field supplies and storage of samples problematic. For example, there usually is not room for a cooler large enough to hold all samples. Field equipment must be carefully packed. An aircraft operating at or near legal gross weight combined with a short landing distance may be a recipe for disaster. Fuel requirements must be carefully monitored when operating in a remote area keeping in mind possible changes in wind speed and direction for the return trip. When flying in remote areas weather conditions may be significantly different from forecast. If conditions deteriorate, the decision to divert to the nearest settlement or out camp must be made without hesitation.

When on the lake, the sampling from an aircraft is constantly at odds with the wind. Generally, sampling occurs at the deepest location of each lake. This usually corresponds somewhere near the middle of the lake- with little protection from the wind. Despite using two anchors, the wind usually causes the aircraft to drift backwards making consistent conductivity/ oxygen/ temperature profiles difficult. On exceptionally windy days, these measurements may be impossible.

When landing on a small or narrow lake, there is significant opportunity for wind shear (sudden changes in wind speed or direction) resulting from downdrafts over the trees or cliffs. Extra airspeed should be carried and caution exercised particularly when faced with a cross wind on a narrow lake with tall trees or steep shores. Even a wind straight down the lake may present a rough ride and encountered downdrafts may significantly reduce ones rate of climb. On calmer days or in the morning, wind direction can switch from landing to take off. Evaluate both ends of a lake to ensure that a takeoff is possible should wind direction suddenly reverse i.e. that there are no 50-foot cliffs at ether end of a small lake with 100-foot trees on top.

2004 and 2005 Climate data for Pinawa

Table 32: Climatic values observed at Pinawa (50° 10' N 96° 3' W) from October 2003 to September 2004.

Pinawa was the nearest active meteorological station and was located 57 km south of the study area. Data courtesy: Environment Canada, Canadian Climate Data available at http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html

	Mean Max Temp	Mean Temp	Normal 1970-2000	Mean Min Temp	Extreme Max Temp	Extreme Min Temp	Total Rain	Total Snow	Total Precip	Normal 1970-2000	Precip Percent Normal
Month	°C	°C	°C	°C	°C	°C	mm	cm	mm	mm	%
Oct	11.3	6.3	5.1	1.4	28.5	-6.0	13.5	9.0	22.5	45.5	49.5
Nov	-1.9	-6.0	-4.9	-10.1	9.0	-20.5	0.0	11.5	11.5	30.6	37.6
Dec	-3.7	-8.5	-14.5	-13.3	5.0	-31.5	9.5	27.5	37.0	23.7	156.1
Jan	-15.9	-21.7	-18.1	-27.4	-6.4	-40.3	0.0	82.6	82.6	21.7	380.6
Feb	-5.7	-11.7	-13.7	-17.6	5.6	-34.8	0.0	11.1	11.1	16.9	65.7
Mar	0.1	-6.1	-6.2	-12.3	10.8	-24.8	0.0	102.0	102.0	27.3	373.6
Apr	7.9	2.3	3.4	-3.4	17.7	-9.0	24.8	0.0	24.8	31.9	77.7
May	11.8	6.5	11.4	1.1	23.4	-4.9	93.0	33.7	126.7	59.5	212.9
Jun	18.3	12.7	16.2	7.1	29.0	1.8	60.2	0.0	60.2	94.5	63.7
Jul	22.5	17.1	18.9	11.7	28.1	5.3	69.8	0.0	69.8	78.3	89.1
Aug	18.7	13.4	17.7	8.0	24.2	1.6	87.0	0.0	87.0	71.5	121.7
Sep	19.1	13.8	11.8	8.6	31.0	2.9	98.6	0.0	98.6	64.1	153.8
TOTAL							456.4	194.8	733.8	565.5	129.8

Table 33: Climatic values observed at Pinawa (50° 10' N 96° 3' W) from October 2004 to September 2005.
Pinawa was the nearest active meteorological station and was located 57 km south of the study area. Data courtesy: Environment Canada Canadian Climate Data available at http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html

Month	Mean Max Temp °C	Mean Temp °C	Normal 1970-2000 °C	Mean Min Temp °C	Extreme Max Temp °C	Extreme Min Temp °C	Total Rain mm	Total Snow cm	Total Precip mm	Normal 1970-2000 mm	Precip Percent Normal %
Oct	10.4	6.1	5.1	1.9	26.0	-8.0	62.1	Trace	62.1	45.5	136.5
Nov	3.9	-0.8	-4.9	-5.4	12.5	-16.0	4.3	11.1	15.4	30.6	50.3
Dec	-9.4	-15.1	-14.5	-20.8	3.5	-39.0	3.0	50.0	53.0	23.7	223.6
Jan	-12.2	-19.1	-18.1	-25.9	1.0	-44.0	Trace	44.5	44.5	21.7	205.1
Feb	-5.7	-12.5	-13.7	-19.3	6.0	-35.0	0.0	7.0	7.0	16.9	41.4
Mar	-0.1	-7.2	-6.2	-14.3	12.0	-30.0	1.0	5.5	6.5	27.3	23.8
Apr	13.4	7.4	3.4	1.3	24.0	-6.5	35.6	Trace	35.6	31.9	111.6
May	16.4	10.5	11.4	4.5	34.0	-5.0	86.6	Trace	86.6	59.5	145.5
Jun	22.4	17.2	16.2	12.0	32.0	7.0	217.9	0.0	217.9	94.5	230.6
Jul	26.2	20.0	18.9	13.8	34.0	5.0	95.4	0.0	95.4	78.3	121.8
Aug	23.5	17.9	17.7	12.3	32.5	4.0	41.8	0.0	41.8	71.5	58.5
Sep	20.3	14.4	11.8	8.5	29.0	0.0	49.2	0.0	49.2	64.1	76.8
TOTAL							596.9	118.1	715.0	565.5	126.4