Dissolved Oxygen Conditions and Fish Requirements in the Athabasca, Peace and Slave Rivers: Assessment of Present Conditions and Future Trends

5

Synthesis Report

Canada Alberta Northwest Territories

Northern River Basins Study

NORTHERN RIVER BASINS STUDY
SYNTHESIS REPORT NO. 5

DISSOLVED OXYGEN CONDITIONS AND FISH REQUIREMENTS IN THE ATHABASCA, PEACE AND SLAVE RIVERS: ASSESSMENT OF PRESENT CONDITIONS AND FUTURE TRENDS

by

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EXECUTIVE SUMMARY

This report addresses the Northern River Basins Study (NRBS) question: "What concentrations of dissolved oxygen are required seasonally to protect the various life stages of fish, and what factors control dissolved oxygen (DO) in the rivers?" Concern about DO conditions in the Northern Rivers focuses on the ice-covered period when only limited reaeration occurs to replenish any oxygen consumed by oxygen-consuming effluent, river biota and naturally-occurring chemical processes. During the remainder of the year, oxygen from the air is incorporated the river water and offsets any losses of oxygen. The report synthesizes results from monitoring, research and modelling studies undertaken as part of the NRBS to characterize loading from all point sources in the Northern River basins, evaluate the impacts of oxygen-consuming waste on river chemistry, develop models for predicting DO concentrations in the Athabasca River, assess the response of riverine biota to low DO levels, and investigate interactions between low DO levels and nutrients and contaminants in pulp mill effluent on benthic organisms. These findings are used to assess the state of aquatic ecosystem health, and develop scientific and management recommendations for the Northern River basins.

During winter ice cover, DO concentrations in the Athabasca, Wapiti and Smoky rivers decrease along the length of the rivers with sags in DO occurring below some pulp mill discharges in certain winters. In the case of the Athabasca River, DO concentrations remain relatively constant and approach saturation from the headwaters to upstream of Hinton. Thereafter, concentrations decrease to Grand Rapids where a 10 m cascade keeps the water open year-round and reaerates DO levels back to saturation. After Grand Rapids, DO concentrations once again begin to decline. Sags in DO were observed below Weldwood of Canada Ltd. in most winters and below Millar Western Pulp Ltd. during the 1989 start-up winter. In the Wapiti-Smoky rivers, DO concentrations decrease from upstream of Grande Prairie to the mouth of the Wapiti River and continue to decrease in the Smoky River. Oxygen depletion is minimal in the mainstem of the Peace River during winter due to low BOD_5 concentrations, reaeration at Vermillion Chutes and perhaps Boyer Rapids, and the fact that the water column is saturated with oxygen as it enters Alberta and the reach from the British Columbia border to Peace River remains ice-free for much of the winter. While longitudinal data on DO concentrations in the Slave River are not available, it is unlikely that there is any appreciable decline in DO concentrations with distance.

Historical data from 1958-1995 for the Athabasca River indicate that late winter DO concentrations downstream of Hinton were lowest during the 20-years following the 1957 start-up of the Hinton mill and have since increased significantly ($P< 0.05$) at both Whitecourt and Athabasca. In the Wapiti-Smoky rivers, winter DO concentrations upstream of Grande Prairie have remained constant before (1966-1972) and after (1973-1992) the start-up of the Weyerhaeuser Canada Ltd. mill but have decreased significantly in the Smoky River since 1973. DO concentrations less than the *Alberta Surface Water Quality Objective* of 5 mg/L DO or the *Canadian Water Quality Guideline* for adult cold-water fish of 6.5 mg/L DO have never been observed on the Wapiti, Smoky or Peace river mainstems and do not routinely occur in the mainstem of the Athabasca River. However, the very occasional DO concentration of < 5 mg/L has been reported for the Athabasca River mainstem in near-shore areas or zones where effluent mixing was not complete. A few tributaries to the Athabasca River (the Pembina, Lac La Biche, Muskeg and Firebag rivers) have DO concentrations less than the 5.0 mg/L objective on a fairly consistent basis.

In addition to water quality monitoring, recent studies of DO in the Athabasca River have expanded to include simulation modelling. Water quality simulations models are important tools for estimating the impact of effluent loadings on river chemistry and biota, and can assist in assessing the effects of existing and future loading scenarios. As part of the NRBS, input parameters for the DO simulation model DOSTOC were tested and validated for their applicability to the Athabasca River. When DOSTOC was implemented using only *in situ* or laboratory measurements for all input parameters (with the exception of temperature correction coefficients), the simulations gave a reasonable fit to the observed data (i.e., r^2 0.74) for January 1989 and the 1990-1994 winters with 70% of the observed DO values falling inside the 90% confidence limits. Discrepancies between predicted and observed DO concentrations usually occurred in sag zones immediately below pulp mill discharges (where DO concentrations were generally over-predicted) and may be due to insufficient information on nitrogenous oxygen demand to allow inclusion of this factor in the modelling. The modelling results indicated that reasonable simulation could be expected for the reach between Hinton and Grand Rapids for the more recent years (1990 - 1994). Poorer predictions in early years (1988 and March 1989) may have related to the limited data on tributary and sewage inputs and mainstem DO concentrations for 1988 and, in March 1989, to the large and erratic BOD loadings from Millar Western Pulp Ltd. which had likely not equilibrated with instream processes.

Experiments were conducted as part of the NRBS to test the effects of lowered DO on larval development of fall or winter spawning fish species common in the Northern Rivers and on survival of the common benthic invertebrate, the mayfly *Baetis tricaudatus*. In the Northern River basins, most fish species spawn in spring. Their eggs incubate during spring or early summer and, thus, the early life stages experience little or no DO limitations. However, several fish species, including mountain whitefish (*Prosopium williamsoni*), bull trout (*Salvelinus confluentus*) and burbot (*Lota lota*) spawn in fall or winter and their eggs incubate during winter with the early life stages occurring in spring and summer. Laboratory experiments showed that DO concentrations as low as 3 mg/L at temperatures of 2-3°C had no effect on egg survival of either mountain whitefish or bull trout; however, mountain whitefish eggs took much longer to hatch and bull trout alevins were less well developed (having consumed proportionately less of their yolk sac) at low DO concentrations. DO concentrations of 6 mg/L may also extend the time required to hatch by some burbot. With respect to the mayfly, a DO concentration of only 5 mg/L was found to decrease survival and feeding rates. Given that mayflies and the early life stages of fish live at or in the surface layers of the riverbed and that DO concentrations can differ by 3 mg/L between the water column and the sediment-water interface, water-column DO concentrations of 6-9 mg/L would be needed to protect these organisms. While detailed investigations of egg incubation and early rearing habitat for fish in the Northern Rivers were not undertaken, it is likely that the sites of egg incubation which experience lowered DO are not extensive and represent negligible quantities of the known and suspected incubation and early rearing habitat for bull trout, mountain whitefish and burbot in the Northern River basins. Consequently, it is unlikely that low DO is having measurable effects on populations of these fish species at present.

On the basis of findings from studies reviewed in this synthesis report, the following key recommendations are proposed:

- regular monitoring and reporting of BOD_5 and flow from sewage treatment plants should be a license requirement. In addition, provision is needed for ensuring compliance with sampling and analytical procedures for all licensed dischargers (industrial and municipal), for ensuring training certified operators to measure (and record) flow rates and discharge volumes, and for enforcement of reporting requirements. Standard reporting requirements for water quality parameters should be established and reporting proper data should be a license requirement.

- a clear definition of the goals of DO simulation modelling and a resolution of input data discrepancies should be undertaken before further modelling is attempted. There appear to be two goals with respect to DO modelling in the Northern River basins: (1) short-term compliance assessments (i.e., predicting DO levels during the upcoming winter), and (2) long-term basin management (i.e., establishing license requirements with respect to changing industrial operations). For both approaches, a probabilistic model should be employed so as to allow assessment of the effect of variances in model input parameters on the confidence of the model predictions. However, basic issues such as validating the Leopold Maddock coefficients used in calculating reach velocities need to be resolved before more complex modelling is attempted. Measured rates should also be employed in DO simulation modelling wherever possible rather than calibration values.

- *in situ* measurements of DO levels in the substratum and water column should be undertaken during winter to assess the DO status of fish and benthic invertebrate habitat and quantify the relationship between substratum and water-column DO concentrations. These measurements should be conducted in conjunction with *in situ* bioassays with eggs of mountain whitefish, bull trout and burbot and measurements of DO, BOD_5, SOD, contaminant occurrence and effects, and ice cover effects.

- the cause of the elevated SOD rates below pulp mill discharges should be established. These higher SOD rates may be due to organic carbon loading or enhanced periphyton growth due to nutrient loading from pulp mills.

- regulatory standards for DO should be reviewed to ensure that they are consistent with the minimal requirements known to be important for the native fishes of the Northern River basins. Given the fact that fish (mountain whitefish and bull trout) and mayflies show chronic oxygen stress at 3 and 5 mg/L DO, respectively, that mayflies and early life stages of fish live at or in the surface layers of the riverbed and that DO concentrations can differ by 3 mg/L DO between the water column and the sediment-water interface, DO concentrations in the Athabasca River could already be at levels that could have chronic effects on these animals at localized sites. Based on the fact that many fall-spawning fish species are in the salmonid family, the more conservative *Canadian Water Quality Guideline* of 6.5 mg/L DO for salmonids is recommended as a policy-based guideline to be used in setting effluent license conditions for periods of ice-cover.

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INTRODUCTION

1.0 INTRODUCTION

The aim of this report is to address the Northern River Basins Study (NRBS) question: "What concentrations of dissolved oxygen are required seasonally to protect the various life stages of fish, and what factors control dissolved oxygen (DO) in the rivers?"

Dissolved oxygen is essential for all aquatic organisms with aerobic respiration. In rivers which experience ice cover, depression of DO during winter is a common occurrence. Severe oxygen depletions were noted as early as the mid-1940's in streams and rivers in Russia (Hynes 1970 after Mosevich 1974; Mossewitsch 1961) while in North America, one of the earlier accounts dates from the 1960's for rivers in Alaska (Schallock and Lotspeich 1974). The cause of dissolved oxygen depletion under ice-cover is generally attributed to three factors: (1) lack of reaeration due to ice cover, (2) inputs of oxygen-depleted groundwater, and (3) oxidation of organic material. However, while the importance of these factors in controlling under-ice depletion has long been recognized, little information is available on the relative roles of these factors and the impact that anthropogenic (i.e., man-made) loading of organic material may have in further depleting winter DO concentrations. Given the large-scale developments planned and underway in many northern rivers throughout the world (e.g., mining, timber harvesting, pulp mills, gas and oil extraction, and changes in landuse patterns), the factors controlling natural declines in DO under-ice need to be identified and quantified in order to improve predictions of the impact of development on winter DO concentrations.

The aim of this report was to assess the loading of oxygen-consuming waste from pulp mills, municipalities and other industrial sources on the Athabasca, Wapiti, Smoky, Peace and Slave rivers and evaluate the impacts of these loads on the biota of these rivers. During the past four years, studies have been undertaken as part of the NRBS to characterize loading from all point sources in the Northern River basins, evaluate the impacts of oxygen-consuming waste on river chemistry, develop models for predicting DO concentrations in the Athabasca River, assess the response of riverine biota to low DO levels, and investigate interactions between low DO levels and nutrients and contaminants in pulp mill effluent on benthic organisms. In this report, the current state of knowledge with respect to DO conditions in rivers during periods of ice cover will be reviewed (Chapter 1) and results from monitoring, research and simulation modelling studies will be synthesized for work undertaken by the NRBS and other agencies operating in the Northern River basins (Chapters 2-6). This information will be used to provide an assessment of the state of aquatic ecosystem health and develop scientific and management recommendations for the Northern River basins (Chapters 7 and 8).

1.1 DISSOLVED OXYGEN CYCLE

Oxygen is essential to the metabolism of most aquatic plants and animals. Aquatic organisms do not breathe air but, instead, extract DO from the water. DO concentrations are expressed as milligrams per litre DO (mg/L DO). The amount of oxygen that can be dissolved in water depends on water temperature, elevation above sea level and salinity. More oxygen can dissolve in cold water than in warm water: at 4oC, one litre of water can hold (or is saturated at) approximately 12 mg of oxygen whereas at 20oC it is saturated at approximately 8 mg/L DO.

Similarly, fresh water holds more oxygen than saline water and saturation increases with increased pressure (i.e., at lower elevations). During winter when water temperatures are approximately 0oC, water in the Athabasca, Wapiti, Smoky, Peace and Slave rivers is saturated at approximately 13.5 mg/L DO.

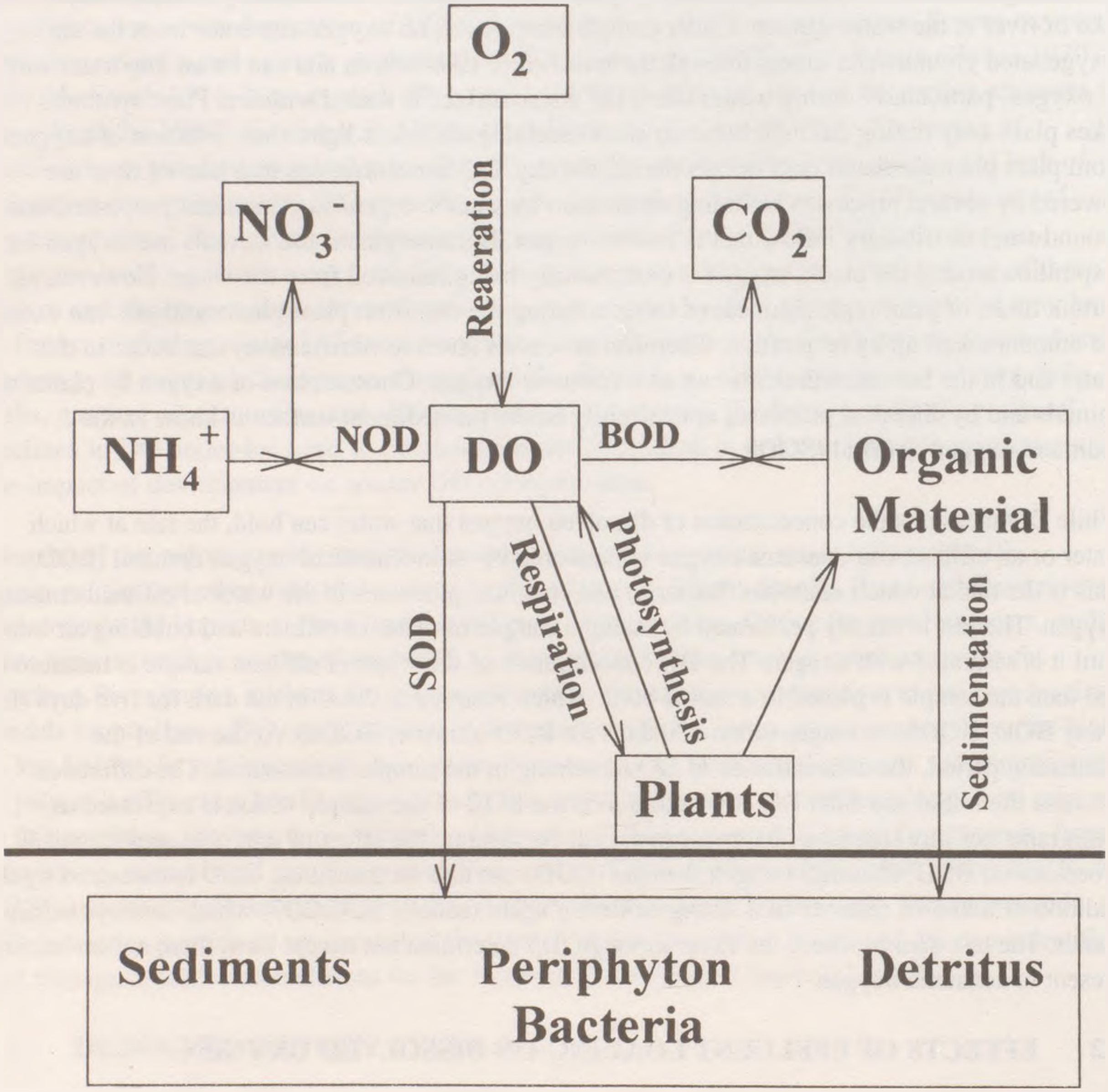
Oxygen enters a lake or river from three sources: from the air, as a byproduct of plant photosynthesis, and with groundwater or tributary inflow (Figure 1.1). Oxygen from the atmosphere can only enter a lake or river at the water surface. Under complete ice-cover, no oxygen can enter from the air. Oxygenated groundwater enters through the riverbed or lake bottom and can be an important source of oxygen, particularly during winter when the water surface is sealed with ice. Photosynthesis takes place only during daylight hours in areas receiving sufficient light; thus, addition of oxygen from plant photosynthesis only occurs during the day. DO concentrations in a lake or river are lowered by several processes including respiration by aquatic organisms, chemical processes, and groundwater or tributary inflow that is low in oxygen. Because plants and animals use oxygen for respiration around the clock, oxygen is continuously being removed from the water. However, at certain times of year, replenishment of oxygen during the day from plant photosynthesis can exceed the amount taken up by respiration. Chemical processes (such as nitrification) that occur in the water and in the bottom sediments can also consume oxygen. Consumption of oxygen by plants and animals and by chemical processes at or slightly below the sediment surface is know as the sediment oxygen demand (SOD).

While DO measures the concentration of dissolved oxygen that water can hold, the rate at which water or an effluent can consume oxygen is measured by its biochemical oxygen demand (BOD). This is the rate at which microbes (bacteria) and chemical processes in the water or effluent consume oxygen. The test is usually performed by taking a sample of water or effluent and bubbling air into it until it is saturated with oxygen. The DO concentration of the water or effluent sample is measured and then the sample is placed in a sealed bottle which is stored at 20oC in the dark for five days (for 5-day BOD, BOD5) or longer (often 120 days for BOD ultimate, BODu). At the end of the incubation period, the concentration of DO remaining in the sample is measured. The difference between the initial and final DO concentration is the BOD of the sample which is expressed as milligrams per litre (mg/L) of oxygen consumed. To separate the effect of microbes and chemical processes on BOD, chemical oxygen demand (COD) can also be measured. COD is measured by the addition of a known quantity of a strong oxidizing agent (usually K2Cr2O7) which destroys organic matter. The test then proceeds the same as for BOD5 determination except now, there are no bacteria present to consume oxygen.

1.2 EFFECTS OF EFFLUENT LOADING ON DISSOLVED OXYGEN

Rivers have a DO regime determined by a balance between reaeration, photosynthesis and respiration, and chemical processing of organic and inorganic matter (Figure 1.1). During the open-water season, atmospheric reaeration is sufficient to maintain DO concentrations near saturation for most of the water in a river (Barton and Taylor 1994). However, localized oxygen depletion can occur in response to summer conditions of high water temperature and aquatic plant respiration (e.g., MacCrimmon and Kelso 1970; Wilcock et al. 1995) or the addition of oxygen-consuming effluent (Abel 1989). The

Figure 1.1 Sources and sinks of dissolved oxygen in rivers.



magnitude of the effluent induced oxygen sag depends on dilution, the BOD of the discharge and of the receiving water, the nature of the organic material, the total organic load in the river, temperature, reaeration, DO of the receiving water and the types of bacteria in the effluent (Mason 1983).

Unlike the open-water season, DO depression on a large scale (both spatial and temporal) occurs regularly under ice cover due to limited reaeration, reduction in photosynthetic activity due to ice cover, oxygen consumption by water-column and sediment organisms, low winter flows and inputs of DO depleted groundwater (Schreier et al. 1980; Babin and Trew 1985). For northern rivers outside of the NRBS area, large-scale longitudinal (100's of kilometers) and temporal (freeze-up to break-up) depressions in under-ice DO have been observed in rivers that are free from effluents: 36 rivers in Alaska (Schallock and Lotspeich1974); Ogilvie and Swift rivers, Yukon (Schreier et al. 1980); and the Takhini and Nordenskiold rivers, Yukon (Whitfield and McNaughton 1986). Similar trends have been found in rivers receiving effluent: Red Deer River, Alberta (Bouthillier and Simpson 1972); Beaver and Sand rivers, Alberta (Babin and Trew 1985); North Saskatchewan River, Alberta (Anderson et al. 1986); Chena River, Alaska (Tilsworth and Bateman 1982); Tu Men River, China (Ranjie and Huimin 1987); and Sukhona River, U.S.S.R. (Brekhovskikh and Volpian 1991). All these rivers showed higher DO concentrations at the headwaters than at the mouths and minimum DO concentrations before spring break-up. Superimposed on these large scale under-ice DO depressions, local DO sags caused by the addition of effluent BOD were noted for the Red Deer River by Bouthillier and Simpson (1972).

1.3 RESPONSES OF AQUATIC ORGANISMS TO LOW OXYGEN CONDITIONS

The concern with lowered DO concentrations in lakes and rivers is their effect on fish and other aquatic organisms. Hypoxia (i.e., the supply of oxygen is below normal) can occur for two reasons: (1) environmental conditions that reduce DO concentrations (e.g., pollutants, degradation of organic matter produced in the stream and its watershed, plant respiration), and (2) malfunctioning of the normal gas exchange process at the gills. All species and life stages of fish have both acute and chronic DO requirements. Acute requirements are the minimal levels of DO necessary to avoid mortality. Chronic requirements are the minimum DO concentrations necessary for long-term growth and reproduction. Under conditions of moderate oxygen stress (i.e., sublethal DO concentrations), changes may occur in physiological processes, blood chemistry and hematology, and result in histopathological damage. Under severe hypoxia (i.e., lethal DO concentrations), insufficient oxygen to the brain and other tissues results in cellular dysfunction and death. Acute DO levels have been well studied for many fish species. For most fish, mortality occurs at between 1 to 3 mg/L DO with survival times of 1 to 3 hours (Doudoroff and Shumway 1970). More difficult to assess and less well known, especially for the species in the Northern Rivers, are the chronic effects of low DO and their implications for long-term growth and survival of northern river fish populations.

There are a variety of physiological mechanisms used by fish to adapt to hypoxia. Some fish species are able to adjust to lower DO through acclimation (Shepard 1955) and metabolic adjustment (Ultsch et al. 1978). Adaptation to hypoxia may also have a genetic basis (Klar et al. 1979 a, b) and appears to be age dependent (Strel'tsova 1964). Physiological adjustments to nonlethal hypoxia may include: bradycardia (decreased heart rate but possibly higher stroke volume), tachycardia (increased heart rate), increased ventilatory rate, reduction of peripheral resistance (i.e., in gills), and recruitment of additional secondary lamellae (Hughes 1973, 1981). Adjustment mechanisms include swelling of erythrocytes (red blood cells) (Soivio and Nikinmaa 1981); increased respiratory volumes (Saunders 1962); increased metabolic rate to bring sufficient amounts of DO in contact with the gills (Jensen et al. 1993); use of catecholamine hormones which increase functional surface area (Booth 1979; Pettersson and Johansen 1982; Boutilier et al. 1988); decrease in urinary volume which reduces ion losses (Kakuta et al. 1992); increased gill ventilation rates (Petrosky and Magnuson 1973); and the use of anaerobic metabolism to maintain energy required for survival (Heath et al. 1980). These adaptive responses come at the cost of other metabolic activities such as somatic and gametic growth (Fry 1947); an upset of the acid-base balance (Hughes 1981); declines in white muscle adenosine triphospohate (Vetter and Hodson 1982); decreased concentrations of free amino acids which reflect a shift away from tissue binding in favor of energy production (Medale et al. 1987); adjustment of normal digestive functions (Boge et al. 1980); and alteration of serum protein patterns which may compromise the fish's ability to compete (Bouck and Ball 1965). There may also be hematological changes including increases in hemoglobin, blood cell count, hematocrit and associated blood paramters (e.g., Scott and Rogers 1981; Tun and Houston 1986; Lochmiller et al. 1989; Marinsky et al. 1990). As well, histopathological damage has been noted in various tissues including the gills (Plumb et al. 1976; Scott and Rogers 1980). Other effects have also been noted such as decreased disease resistance (Grizzle 1981; Angelidis et al. 1987; Giles 1987; Jensen et al. 1993); reduction in growth rates (Adelman and Smith 1970; Brett and Blackburn 1981; Chapman 1986); and a decrease in swimming speed (Dahlberg et al. 1968; Kutty 1968; Jones 1971; Bushnell et al. 1984). Changes in fish behaviour due to hypoxia are numerous and can be divided into four classes: (1) change in activity, (2) change in habitat (vertical and horizontal), (3) increase in air-breathing, and (4) increase in aquatic surface breathing (Kramer 1987). The sum of all the biochemical, physiological and behavioural changes induced by hypoxia may be reflected at the population or community level.

In addition to the direct effects of hypoxia, reduced concentrations of DO increase the toxicity of most contaminants (Barton and Taylor 1994). This has been observed with a number of chemicals (i.e., ammonia (Thurston et al. 1981); 1,2,4-trichlorobenzene (Carlson 1987)) and can be extended to pulp mill effluent and its conponents (Hicks and DeWitt 1971). As DO concentrations decline, resin acids, the principal toxicant in effluent from mills pulping softwoods, become more toxic by interfering with normal O2 uptake by the gill lamellae and inducing O2 starvation (Taylor et al. 1988). With the physical damage to gill tissues, fish can suffer hypoxic effects even though ambient DO levels may otherwise be adequate. Other interactive effects of mill effluent and low DO include: hormonal responses (Hughes 1981); reduced hatching success (Tana and Nikunen 1986); and survival of juvenile fish (Graves et al. 1981). There has also been evidence of lowered hatching success due to increased benthic algal mats downstream of mill effluents (Colby and Smith 1967). Suspended wood fibre was found to decrease active metabolism, reduce swimming endurance, increase maintenance energy requirements and increase blood hematocrit of flathead minnows (MacLeod and Smith 1966). Other sublethal effects include elevated frequency of "coughing", reduced O2 saturation in arterial blood, changes in blood chemistry, depression of liver glycogen storage, increased ventilation, less vigorous feeding, decreased growth and food conversion efficiency, and avoidance behaviours (Barton and Taylor 1994). Responses at the community level have also been documented such as species shifts (Kelso 1977) and disruption in natural year-class patterns (Bohling et al. 1991). The similarity between responses to pulp mill effluent and hypoxia suggest that a general stress response is being manifested (Barton and Taylor 1994).

1.4 OBJECTIVES OF THIS REPORT

This report presents a synthesis of results from studies on the impacts of BOD loading on the Athabasca, Wapiti, Smoky, Peace and Slave rivers as undertaken by the NRBS and other agencies operating in the Northern River basins. The report addresses:

- the identification and regulation of point sources of BOD loading (Chapter 2)
- changes in river-water DO concentrations in response to BOD loading (Chapter 3)
- implementation of simulation models to predict winter DO concentrations in the Athabasca River (Chapter 4)
- the DO requirements of fish in the Northern River basins (Chapter 5)
- interactions between low DO levels and nutrients and contaminants in pulp mill effluent on benthic organisms (Chapter 6).

The information obtained from these studies is then integrated to provide an assessment of the state of aquatic ecosystem health (Chapter 7) and develop scientific and management recommendation for the Northern River basins (Chapter 8).

CHAPTER 2.0

IDENTIFICATION AND REGULATION OF POINT SOURCES OF BOD LOADING

2.0 IDENTIFICATION AND REGULATION OF POINT SOURCES OF BOD LOADING

The NRBS area encompasses the Athabasca, Peace and Slave river drainage basins that lie within Alberta and the North West Territories. The Athabasca River receives effluent from 15 continuous-discharge point sources (five pulp mills, one oil sands project and nine municipalities with one mill and one municipality having a combined discharge). The Wapiti River receives effluent from two continuous-discharge point sources (a pulp mill and a municipality) while the Smoky River receives continuous-discharge effluent from the Wapiti River sources as well as from one additional municipality. The Peace River receives effluent from five pulp mills (two in the NRBS area) and four sources of continuous-discharge sewage, in addition to the sources on the Wapiti-Smoky rivers. The Slave River receives effluent from all the Peace and Athabasca sources as well as from one continuously-discharging sewage treatment plant (STP).

The purpose of this chapter is to characterize the sources of BOD loading to each river in the NRBS area. Daily discharge and daily or thrice-weekly measurements of BOD5 concentrations are collected by all pulp mills as part of the licensing requirements. These data have been compiled in the NRBS Northdat database (McCubbin and AGRA Earth and Environmental 1995) and summarized in McCubbin and Folke (1993), McCubbin et al. (1994) and Lindsay and Smith (1995). Municipalities with continuous discharge in the Alberta portion of the Northern River basins are required to measure discharge daily and BOD5 daily or weekly. Towns with wastewater stabilization ponds are required to measure BOD5 once during the period of discharge. Fort Smith in the Northwest Territories monitors discharge daily and BOD5 monthly. The municipal data have been compiled in the NRBS Municipal and Non-Pulp Mill Industrial Effluents database (Sentar Consultants Ltd. 1995).

2.1 IDENTIFICATION OF POINT SOURCE LOADING

2.1.1 Athabasca River

The Athabasca River originates in the Rocky Mountains of west-central Alberta in Jasper National Park. It then flows northeast across the boreal foothills and boreal mixedwood ecoregions of Alberta to Lake Athabasca where it joins with the Peace River to form the Slave River (Figure 2.1). The Athabasca River is not regulated. Mean daily flows at the Town of Athabasca average 407 m3/s (1980-1993) with peak flows occurring in June after mountain snow-pack melt (1016 m3/s June monthly mean, 1980-1993) and lowest flows in February (62 m3/s February monthly mean, 1980-1993) (Environment Canada 1994).

Concern about water quality in the Athabasca River dates from the 1950's when the first pulp mill became operational. Currently, nine municipalities (as well as Hinton which has a combined discharge with Weldwood of Canada Ltd.) discharge continuously to the Athabasca River or its tributaries, producing a total loading to the river of >541 kg/d BOD5 (Table 2.1). In addition, 40 communities and two oil sands extraction plants discharge sewage lagoons once or twice yearly (fall and sometimes spring) to rivers, creeks and lakes in the Athabasca drainage basin (Alberta Environmental Protection

Figure 2.1 The Athabasca, Peace and Slave river systems showing locations of municipal, pulp mill and industrial discharges.

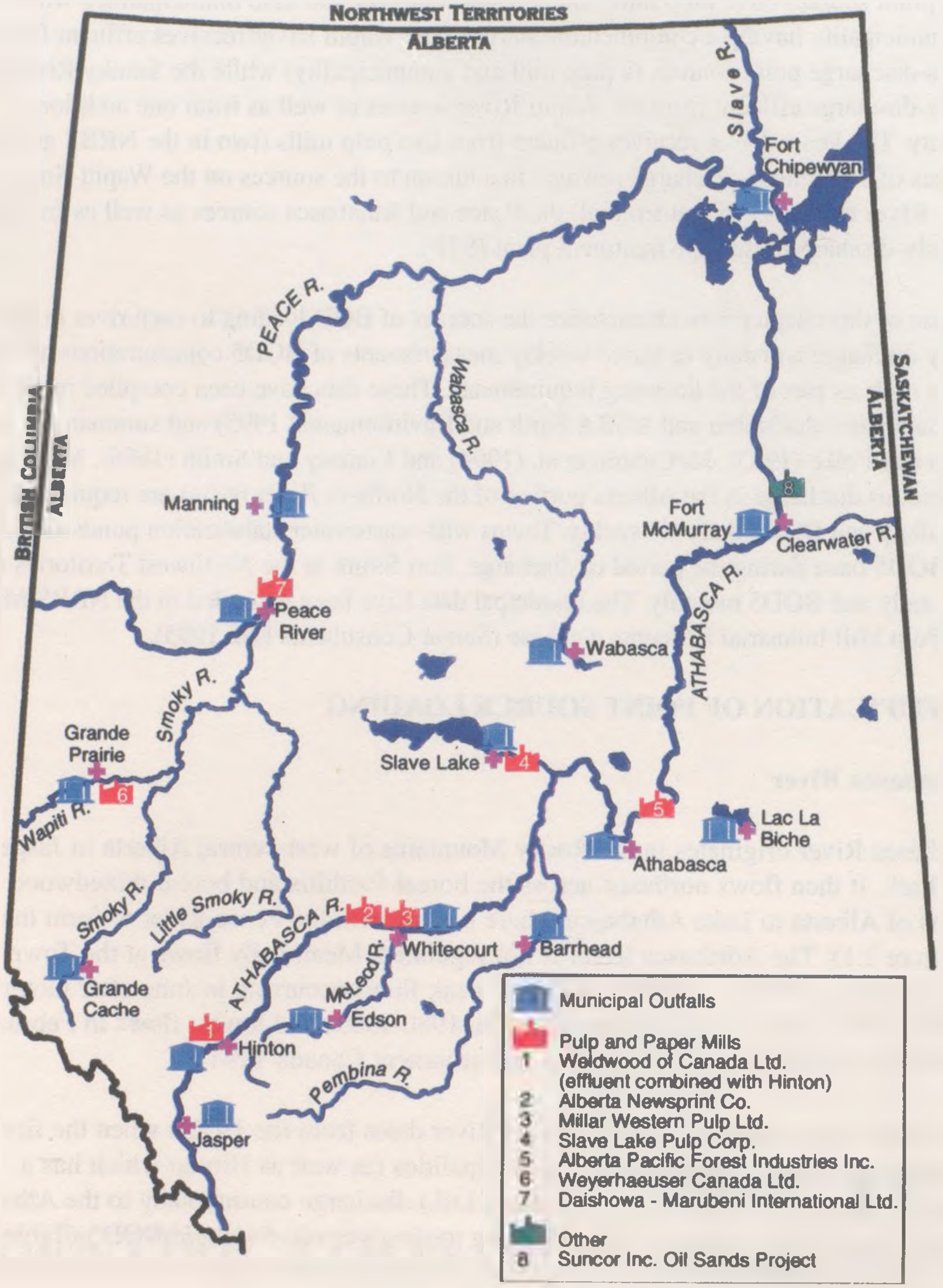


Table 2.1 **Effluent discharge and BOD5 loads for municipalities with continuous discharge in the NRBS area. Discharge data and BOD5 concentrations from the NRBS Municipal and Non-Pulp Mill Industrial Effluents Database (Sentar Consultants Ltd. 1995). BOD5 concentrations were multiplied by mean discharge to give loads (kg/d). Note: Hinton municipal effluent is discharged with Weldwood of Canada Ltd. effluent; N/A is not available. Population data from Statistics Canada (1992). Means, standard errors, years of data and n are contained in Appendix A.**

Source	Population (in 1991)	Effluent Treatment	Receiving Water	BOD_5 (kg/d)	Discharge (m^3/d)
Athabasca River					
Jasper	3619	aerated stabilization basin	Athabasca River	82.7	3948
Edson	7323	aerated stabilization basin	McLeod River	58.6	3954
Whitecourt	6938	extended aeration activated sludge	Athabasca River	34.1	3417
Barrhead	4160	aerated stabilization basin	Paddle River	N/A	N/A
Slave Lake	5607	aerated stabilization basin	Lesser Slave River	49.3	2729
Athabasca	1965	aerated stabilization basin	Athabasca River	13.8	952
Lac La Biche	2549	aerated stabilization basin	Field Lake	35.7	1425
Fort McMurray	3476	aerated stabilization basin	Athabasca River	311	14000
Fort Chipewyan	537	facultative lagoons	Riviere des Rochers	N/A	N/A
Peace River					
Grande Cache	3842	extended aeration activated sludge	Smoky River	7.7	2032
Grande Prairie	2821	rotating biological contactor	Wapiti River	92.6	10728
Peace River Correctional Institute	N/A	oxidation ditch, disinfection	Peace River	1.8	286
Peace River	6717	anaerobic lagoon	Peace River	N/A	N/A
Manning	N/A	aerated stabilization basin	Notikewin River	9.6	487
Wabasca	890	aerated stabilization basin, disinfection	North Wabasca Lake	1.2	245
Slave River					
Fort Smith	2480	facultative lagoons	Slave River	49.2	480

1995). One community (Lac la Biche) has continuous discharge of primary-treated effluent to a small lake (Field Lake) in the watershed.

In 1957 North Western Pulp and Power Ltd. (now Weldwood of Canada Ltd.) commenced operations in Hinton (Table 2.2). The mill is a bleached kraft plant and up to 1966, discharged minimally-treated effluent (i.e., from a facultative settling pond). Changes in operating licenses and mill technology have reduced effluent loading from the mill. In 1967, a primary clarifier (for removing solids) and aerated lagoons (five-day retention time) were installed to provide secondary treatment, with the latter expanded in 1975. The largest change occurred in 1990 when oxygen delignification and chlorine dioxide substitution were introduced and the effluent clarifier and aerated lagoons upgraded; 100% chlorine dioxide substitution was achieved in June 1993. Between August 1988 and late 1990, three chemi-thermomechanical mills started operations in the basin (Table 2.2); another kraft mill (Alberta Pacific Forest Industries Inc.) became operational in September 1993. BOD5 loads to the river from all mills totalled 4828 kg/d (1990 - 1993; Table 2.2). There are also two oil sands projects in the basin but only one (Suncor Inc. Oil Sands Group) with continuous discharge of utility wastewater (from settling and retention basins plus American Petroleum Institute (API) separation system for oily wastewater) (Table 2.3). Other activities in the basin include four active coal mines, 67 gas plants, another oil sands project and 12 gravel-washing enterprises; however, all have little or no discharge (Alberta Environmental Protection 1995).

2.1.2 Wapiti-Smoky River

The Wapiti River arises in the Rocky Mountains of east-central British Columbia, south of Dawson Creek (Figure 2.1). It then flows east across the boreal uplands, boreal foothills and boreal mixedwood ecoregions of Alberta and converges with the Smoky River 42 km downstream of Grande Prairie. The Wapiti River is not regulated. Mean daily flows at Grande Prairie average 88 m3/s (1980-1993) with peak flows occurring in June after mountain snow-pack melt (297 m3/s June monthly mean, 1980-1993) and lowest flows in February (12 m3/s February monthly mean, 1980-1993) (Environment Canada 1994).

The Smoky River originates in the Rocky Mountains of west-central Alberta, northwest of the Town of Jasper (Figure 2.1). It then flows northeast across the boreal uplands, boreal foothills and boreal mixedwood ecoregions of Alberta and is joined by the Wapiti River. The Smoky River continues north and drains into the Peace River at the Town of Peace River. The Smoky River is not regulated. Mean daily flows near Watino average 315 m3/s (1980-1993) with peak flows occurring in June after mountain snow-pack melt (921 m3/s June monthly mean, 1980-1993) and lowest flows in February (43 m3/s February monthly mean, 1980-1993) (Environment Canada 1994).

The only source of continuous-discharging industrial effluent on the Wapiti River is the Weyerhaeuser Canada Ltd. (formerly Procter and Gamble Cellulose Ltd.) bleached kraft pulp mill at Grande Prairie (Table 2.2). The mill began operations in 1973 and discharged effluent treated in a primary clarifier and aerated lagoons. Upgrades to the mill included a switch from 25 to 70% chlorine dioxide substitutionin

Table 2.2 BOD5 loads from pulp mills in the NRBS area. BOD5 loads were obtained for 1990-1994 from the Northern River Basins Study database Northdat (McCubbin and AGRA Earth and Environmental 1995). Means, standard errors, years of data and n are contined on Appendix A.

Pulp Mill	Location	Type	Start Up	Effluent Treatment	BOD_5 (kg/d)
Weldwood of Canada Ltd.	Hinton	Kraft Pulp Expansion in 1990	1957	ASB[1]	2309
Alberta Newsprint Company	Whitecourt	CTMP[2]	Aug. 1990 and paper	Extended aeration AST[3]	161
Millar Western Pulp Ltd.	Whitecourt	CTMP	Aug. 1988	Extended aeration AST	768
Slave Lake Pulp Corp.	Slave Lake	CTMP	late 1990	AST	654
Alberta Pacific Forest Industries Inc	Athabasca	Kraft Pulp	Sept. 1993	AST	936
Weyerhaeuser Canada Ltd.	Grande Prairie	Kraft Pulp	1973	ASB	2066
Daishowa-Marubeni International Ltd.	Peace River	Kraft Pulp	July 1990	ASB	1565

[1] Aerated stabilization basins

[2] Chemi-thermomechanical pulp

[3] Activated sludge treatment

Table 2.3 **Effluent discharge and BOD_5 loads for non-pulp mill industries with continuous discharge in the NRBS area. Discharge data presented as mean ± standard error (years of data; *n*). BOD_5 concentrations for Suncor Inc. Oil Sands Group were obtained from Alberta Environment winter water quality surveys (1989-1994) and multiplied by mean discharge to give load. N/A is not available.**

Source	Start Up	Effluent Treatment	Receiving Water	BOD_5 (kg/d)	Discharge (m^3/d)	Reference
Suncor Inc. Oil Sands Group	1967	retention basin + American Petroleum Institute (API) separation system for oily wastewater	Athabasca River	170	35020±246 (Jan91-Jan93, *n*=1458)	NRBS *Municipal and Non-Pulp Mill Effluents Database* (Sentar Consultants Ltd. 1995).
Alberta Power Ltd. H.R. Milner Thermal Electric Generating Station	N/A	process wastewater	Smoky River	N/A	1469	Shaw *et al.* (1990) after Nagendran *et al.* (1989)
Peace River Oils #1	1916[4]	flowing well	Peace River	N/A	3456 (May88-Mar89, *n*=4)	Alberta Environment (1989)

[4] Peace River Oils #1 abandoned in the mid-1950's (Alberta Environment 1989).

fall 1990 and then to 100% substitution in July 1992. In addition to the pulp mill, there are two municipalities with continuous discharge to the basin: Grande Prairie (which discharges for a two-week period followed by a two-week hold-back) to the Wapiti River and Grande Cache to the Smoky River (Table 2.1). There are also 28 other communities in the Wapiti-Smoky drainage basin which discharge sewage lagoons once or twice yearly to the rivers and their tributaries (Alberta Environmental Protection 1995). The Alberta Power Ltd. H.R. Milner Thermal Electric Generating Station near Grande Cache discharges process wastewater to the Smoky River (Table 2.3). It has a continuous discharge which has been monitored since 1977 (Sentar Consultants Ltd. 1995). There are also 20 natural gas processing plants in the Wapiti-Smoky drainage (Alberta Environmental Protection 1995).

2.1.3 Peace River

The Peace River originates in northeastern British Columbia, flows through Williston Reservoir and the Bennett Dam, and enters Alberta west of the Town of Peace River. From there, the river flows northeasterly across Alberta and drains into the Slave River north of Fort Chipewyan (Figure 2.1). Mean daily flows at Peace Point average 2090 m3/s (1970-1993) with peak flows occurring in June (3608 m3/s June monthly mean, 1970-1993) and lowest monthly flows in March (1426 m3/s March monthly mean, 1970-1993) (Environment Canada 1994). Flows are maintained at high levels during winter (1531 m3/s November-March, 1970-1993) for power generation.

The entire Peace River basin is sparsely populated and largely undeveloped. In addition to Grande Prairie and Grande Cache on the Wapiti-Smoky rivers, the other sources of continuous sewage discharge within the NRBS area are the Town of Peace River and Peace River Correctional Institute (which discharge to the Peace River), Manning (which discharges to the Notikewin River) and Wabasca (which discharges to North Wabasca Lake) (Table 2.1). As well, there are 29 other communities which discharge sewage periodically (fall and sometimes spring) to rivers, creeks and lakes in the Peace River basin (Alberta Environmental Protection 1995). The sources of industrial wastewater to the Alberta portion of the Peace River are the Daishowa-Marubeni International Ltd. mill near the Town of Peace River, the Weyerhaeuser Canada Ltd. pulp mill in Grande Prairie, and the Alberta Power Ltd. H.R. Milner Thermal Electric Generating Station near Grande Cache (Tables 2.2 and 2.3). The Daishowa-Marubeni International Ltd. mill is a bleached kraft mill. It began operations in July 1990 and discharges effluent treated in aeration stabilization basins to the Peace River approximately 19 km downstream of the Town of Peace River. In addition, water from flowing abandoned oil wells may affect surface water quality although evidence for Peace River Oils #1 shows the effect on water quality is limited to increased salt concentrations 100 m below the outfall (Alberta Environment 1989). Agriculture is also a major economic activity in the Peace River basin particularly around Grande Prairie, Valleyview, High Prairie, Fairview, the Town of Peace River and, to a lesser extent, in the High Level-Fort Vermilion district (PRRPC 1982). There are also 40 natural gas processing plants in the Peace drainage (Alberta Environmental Protection 1995).

2.1.4 Slave River

The Slave River originates in northeastern Alberta from the confluence of the Peace and Athabasca Rivers (Figure 2.1). It flows northwest approximately 340 km where it drains into Great Slave Lake. The Slave River is not regulated although its major tributary, the Peace River, is regulated. The Slave River basin is scarcely populated. The only source of continuous effluent discharge to the river is the Town of Fort Smith in the Northwest Territories (Table 2.1).

2.2 REGULATION OF DISSOLVED OXYGEN IN SURFACE WATERS AND BOD IN INDUSTRIAL AND MUNICIPAL EFFLUENTS

2.2.1 Ambient Waters

The Canadian Water Quality Guidelines (CCREM 1987) for DO are shown in Table 2.4. The concentrations represent water-column values and allow for a 3 mg/L difference in DO concentrations between the water column and the interstitial waters. The guidelines were derived from U.S. EPA (1986) criteria for DO expressed as mean (7 and 30 day) and minimum (7 and 1 day) values for cold and warm water species in either early or other life stages. The Canadian Water Quality Guidelines (CCREM 1987) DO requirement for cold water species is based on findings from studies with salmonids. Smelts, pikes and sculpins are presumed to be at least as sensitive as salmonids; walleye and smallmouth bass are considered moderately sensitive. When none of these fish species are present, the warm-water guidelines are to be applied. The guideline for early life stages is to be applied from spawning through to 30 days after hatching.

The Alberta Environmental Protection and Enhancement Act provides for the development of guidelines and ambient environmental quality objectives for Alberta. Prior to the Environmental Protection and Enhancement Act, the Alberta Surface Water Quality Objectives (Alberta Environment 1977) were established with the aim of protecting the most sensitive water use. Possible uses included raw water supply for treated drinking water, propagation of fish and other aquatic life, contact and non-contact recreational activities, and agriculture. The Alberta Surface Water Quality Objectives (Alberta Environment 1977) are also used to set wastewater emission standards so as to protect receiving waterbodies. With the establishment of the Environmental Protection and Enhancement Act in 1993, all Alberta Surface Water Quality Objectives (Alberta Environment 1977) were carried forward under the new Act. The Alberta Surface Water Quality Objective (Alberta Environment 1977) for DO is 5 mg/L. This is based on the earlier U.S. EPA (1986) recommendation of 5 mg/L. It should be noted that the Alberta Surface Water Quality Objectives (Alberta Environment 1977): (1) “apply to surface water except in areas of close proximity to outfalls”, (2) do not apply “where the natural water quality of a lake or river does not meet some of the suggested limits”, and (3) are not legal statutes (only limits as given in effluent discharge licences are recognized as enforceable environmental control laws by the provincial government). Moreover, while the Alberta Surface Water Quality Objectives (Alberta Environment 1977) are provincial in scope, reach-specific guidelines are also set on a case-by-case basis from an assessment of instream flow needs.

Table 2.4 ***Canadian Water Quality Guidelines*** **(CCREM 1987) for dissolved oxygen in the water column.**

Categories of Biota	Dissolved Oxygen Concentration (mg/L)	
	Early life stages[1]	**Other life stages**
Warm-water[2]	6	5
Cold-water	9.5	6.5

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[1] Early life stage guidelines apply from spawning through to 30 days after hatching.

[2] Warm-water guidelines apply when salmonids, smelts, pike, sculpins, walleye and smallmouth bass are not present.

The Government of the Northwest Territories follows the Canadian Water Quality Guidelines (CCREM 1987) for DO.

2.2.2 Effluent Permit Limits

The federal Department of Fisheries and Oceans Canada is responsible for the Pulp and Paper Effluent Regulations under the Fisheries Act. The regulations allow pulp mills to release "deleterious substances" to waterbodies if the quantity does not exceed the maximums specified in the regulations. Monitoring of BOD in the effluent is required under the regulations. In addition, the requirements for environmental effects monitoring as defined by Environment Canada and Department of Fisheries and Oceans (1992) include monitoring of BOD in the effluent and DO concentrations in the receiving water.

Effluent permit limits for industries are shown in Table 2.5 and are stipulated in operating licences. In addition, all licenses contain a clause in which the Director, Standards and Approvals Division, Alberta Environmental Protection reserves the right to modify loading limits. Based on DO simulation modelling (Macdonald and Hamilton 1989), effluent permit levels were set in 1989 at 3 kg BOD5/air-dried tonne (Adt) for all pulp mills except Alberta Pacific Forest Industries Inc.which was set at 1.5 kg BOD5/Adt. To allow technological upgrades by the mills to meet these new standards, flow-rated standards were applied during the 1989-1993 winters after which the new BOD5 limits applied. In addition to pulp mills, other industries in the Northern Rivers basin with permit limits related to oxygen are Suncor Inc. Oil Sands Group (COD limit; Table 2.5) and natural gas processing plants (50 mg/L BOD5). Coal mining/processing facilities and the Alberta Power Ltd. H.R. Milner Thermal Electric Generating Station have no permit limit for BOD5.

Municipalities in Alberta are required to monitor BOD5 concentrations of their effluent. Within the Northern Rivers basins, the municipalities of Athabasca, Barrhead, Edson, Fort McMurray, Jasper, Manning, Slave Lake, Valleyview, Lac La Biche and Wabasca discharge sewage continuously (except for Valleyview which discharges approximately three times per year) from mechanical wastewater systems with aerated lagoons and are required to monitor BOD5 weekly (or, in the case of Valleyview, during periods of discharge), with a permit limit of 20 or 25 mg/L BOD5. Grande Cache, Grande Prairie, Peace River Corrections Centre and Whitecourt discharge sewage continuously (except Grande Prairie which discharges for two weeks followed by a two-week holdback) from mechanical wastewater systems with rotating biological contactors, activated sludge or extended aeration systems and are required to monitor BOD5 daily, with a permit limit of 20 or 25 mg/L BOD5. Towns with wastewater stabilization ponds have no permit limits with respect to BOD loading but are required to measure BOD5 once during the period of discharge (usually fall and sometimes spring although Fort Chipewyan and the Town of Peace River have continuous discharge).

Fort Smith discharges sewage continuously to the Slave River from a three-celled lagoon. The effluent permit limit for BOD5 is 180 mg/L for an average of the past four analytical results. BOD5 monitoring is required monthly as stipulated in the operating license.

Table 2.5 Permitted BOD5 loads and BOD5 monitoring requirements for pulp mills and other industries discharging to the Athabasca, Lesser Slave,Wapiti and Peace rivers. 1958-1988 permitted loads for Weldwood of Canada Ltd. from Anderson (1989); 1989 - 1995 permitted loads from I. Mackenzie, Alberta Environmental Protection and Alberta Environmental Protection (1995).

Industries	Permitted BOD$_5$ Load (expressed as the mean of daily values over one month[7])	BOD$_5$ Monitoring Requirements
Weldwood of Canada Ltd.	1958-1965: 10545 kg/d 1965-1966: 13636 kg/d winter; 22727 kg/d rest of year 1967-1976: 13636 kg/d winter; 22727 kg/d rest of year 1977-1980: 8.7 kg BOD5/Adt[8] @ 520 Adt/d and not to exceed 4524 kg/d BOD5 1980-1988: 6600 kg/d BOD5 1989: 7 kg BOD5/Adt @ 565 Adt/d 1990-1992: 7 kg BOD5/Adt @ 1100 Adt/d 1993-Jan. 1997: 3300 kg/d BOD5. If flow at Hinton < 17 m3/s, then 2590 kg/d.	3 BOD5 composite samples per week (as of Dec. 1994)
Millar Western Pulp Ltd.	1989-1992: 7.5 kg BOD5/Adt @ 680 Adt/d 1993-1994: 2040 kg/d BOD5. If flow at Hinton <17 m3/s, then 1600 kg/d. Nov. 1994-Nov. 2003: 2040 kg/d BOD5. If flow at Hinton <17 m3/s, then 1600 kg/d.	3 BOD5 composite samples per week (as of Nov. 1994)
Alberta Newsprint Company	1990-1993: 3.0 kg BOD5/Adt @ 700 Adt/d 1993-1995: 2100 kg/d BOD5. If flow at Hinton <17 m3/s, then 1650 kg/d. Jul. 1995-Jul. 1997: 2100 kg/d BOD5. If flow at Hinton <17 m3/s, then 1650 kg/d.	1 BOD5 composite sample per day
Slave Lake Pulp Corp.	1990-1993: 3.0 kg BOD5/Adt @ 350 Adt/d May 1995-Oct. 2004: 1050 kg/d BOD5	3 BOD5 composite samples per week (as of Oct. 1994)
Alberta Pacific Forest Industries In	Dec. 1993-1996: 2250 kg/d BOD5	1 BOD5 composite sample per day
Weyerhaeuser Canada Ltd.	1993: 4510 kg/d BOD5 1994: 4100 kg/d BOD5 1995-1996: 2460 kg/d BOD5	3 BOD5 composite samples per week (as of Aug. 1995)
Daishowa-Maruben International Ltd.	Jul. 1995-Apr. 1998: 5500 kg/d BOD5	3 BOD5 composite samples per week (as of July 1995)
Suncor Inc. Oct. Oil Sands Group	1992-1996: 1200 kg/d COD for wastewater discharged from outfall weir; 200 mg/L COD from drainage systems (up for licence renewal in 1996)	3 COD samples per week from outfall weir; daily COD from drainage systems when discharging
Syncrude Canada Ltd.	Jul. 1992-1995: no discharge from tailings pond but 25 mg/L BOD5 limit for wastewater lagoon (up for licence renewal in 1995)	1 BOD5 grab sample per week

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[1] In addition to monthly mean values, daily maximum values are licensed and these are generally twice the monthly average.

[2] Air dried tonne

CHAPTER 3.0
LONGITUDINAL PATTERNS IN DISSOLVED OXYGEN

3.0 LONGITUDINAL PATTERNS IN DISSOLVED OXYGEN

The purpose of this chapter is to review longitudinal changes in DO concentrations in the Athabasca River, Wapiti-Smoky rivers, mainstem of the Peace River, and the Slave River in relation to pulp mill and municipal loadings. Longitudinal changes in DO during winter low flows in the Athabasca River downstream of Hinton were examined by Noton and Shaw (1989) for 1988 - 1989 and Noton and Allan (1994) for 1990-1993. Longitudinal changes in DO concentrations were also examined in the Wapiti-Smoky rivers for the winters of 1987-1991 (Noton 1992) and the Peace River for 1980-1989 (Shaw et al. 1990). Chambers et al. (1996) reviewed longitudinal changes in DO concentrations for the Athabasca River near Jasper and long-term (40 year) changes in DO concentrations for the Athabasca River. It should be noted that all these DO measurements represent water-column values, usually from the middle of the channel. Thus, these values are likely not indicative of DO conditions near the riverbed where benthic invertebrates and larval fish occur. DO concentrations may differ by 3 mg/L between the water column and the interstitial water of a gravel riverbed (U.S. EPA 1986).

3.1 LONGTERM DATA

3.1.1 Athabasca River

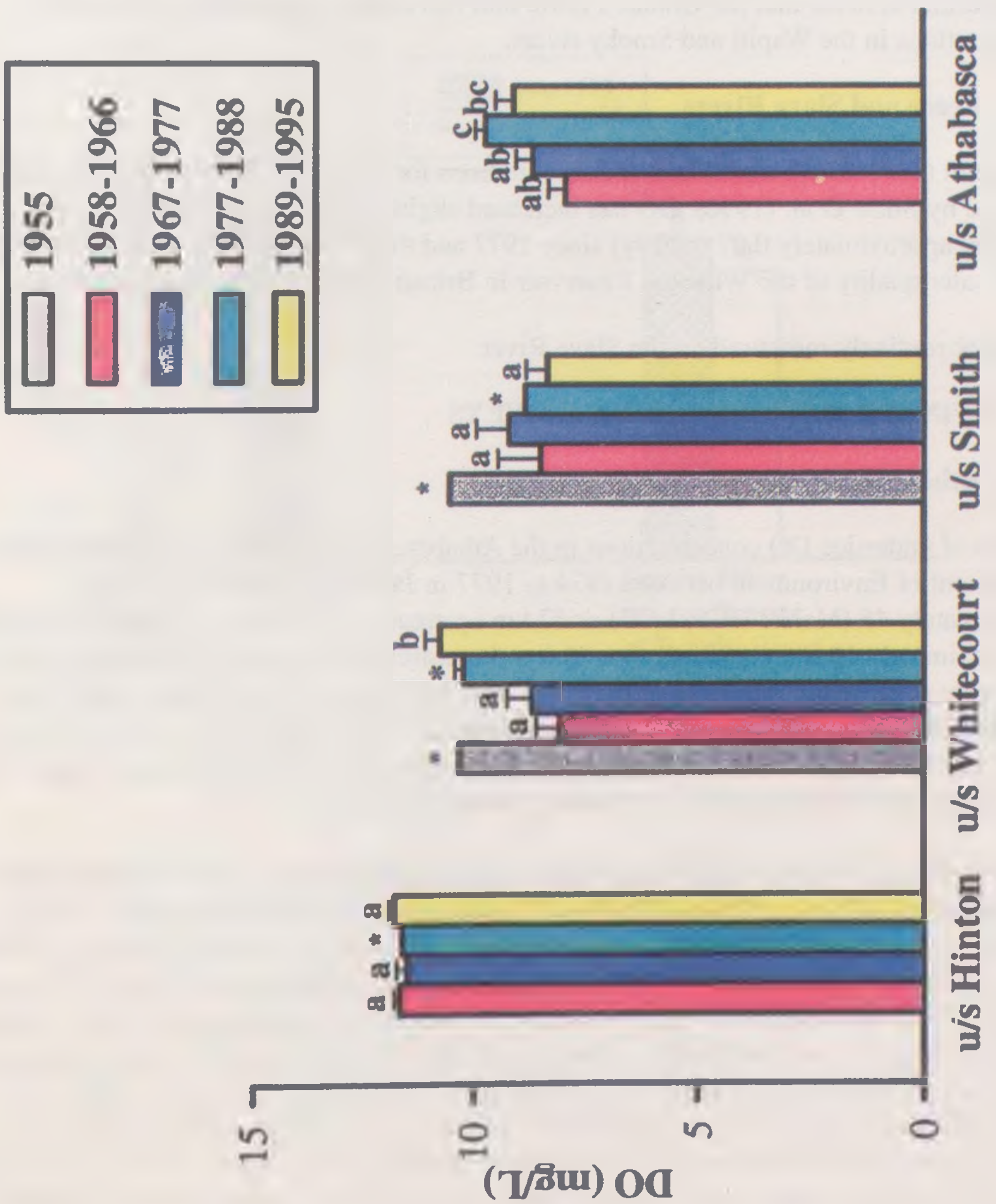
DO concentrations in the Athabasca River have been monitored since 1955, initially by the Alberta Department of Health and, more recently, by provincial and federal departments of environment. Much of the data are available through the Province of Alberta NAQUADAT database; however, the older data (prior to 1970) had never been compiled. As part of the NRBS, historic BOD5 and DO data along with temperature measurements were compiled and loaded into the provincial NAQUADAT database. While there are approximately 23 sites with sporadic DO data prior to 1970, samples were routinely collected from 1958-1995 for four locations: upstream of Hinton, upstream of Whitecourt, upstream of Athabasca, and upstream of Smith.

Chambers et al. (1996) examined the historic database to evaluate long-term (40 yr) changes in DO concentrations at four sites in the Athabasca River. February and March data from a single year and site were averaged to give a late winter DO concentration. Late winter DO concentrations were then averaged for four time periods: 1958-1966, 1967-1976, 1977-1988 and 1989-1995 corresponding to total pulp mill BOD5 loads of approximately 24000, 11344, 3458 and 5045 kg/d (Table 3.1). In addition, data were also presented from upstream of both Whitecourt and Smith prior to the start-up of the mill at Hinton although there was only one year of pre-operational data (1955). They found that late winter DO concentrations upstream of the Hinton effluent outfall have not changed significantly ($P = 0.6$) since 1958 (11.6±0.1; mean±S.E.; n=23) (Figure 3.1). In contrast, DO concentrations downstream of Hinton were lowest during the 20-years following the 1957 start-up of the Hinton mill and have since increased significantly ($P< 0.05$) at both Whitecourt and Athabasca. DO concentrations at Smith have not, however, increased ($P > 0.5$) in recent years. Only one year of data is available prior to the 1957 start-up of the Hinton mill; these limited data suggest that DO concentrations were higher prior to the mill start-up.

Table 3.1 BOD5 loads from pulp mills discharging to the Athabasca River and its tributaries. Loads (mean ± standard error (n)) were calculated as the average of annual means from data in Anderson (1989) for 1958-1976 and Northdat (McCubbin and AGRA Earth and Environmental 1995) for 1977-1993.

Years	Mills Operating	BOD_5 Load (kg/d)
1958-1966	Weldwood of Canada Ltd.	24000
1967-1976	Weldwood of Canada Ltd.	11344 ± 841 (*n* = 10)
1977-1988	Weldwood of Canada Ltd.	3458 ± 233 (*n* = 11)
1989-1995	Weldwood of Canada Ltd., Millar Western Pulp Ltd., Alberta Newsprint Co., Slave Lake Pulp Corp., and Alberta Pacific Forest Industries Inc.	5045 ± 770 (*n* = 5; data for 1989-1993 only)

Figure 3.1 Late winter (February/March) dissolved oxygen (DO) concentrations in the Athabasca River immediately upstream of Hinton, Whitecourt, Smith and Athabasca for five time periods (1955, 1958-1966, 1967-1976, 1977-1988 and 1989-1995) corresponding to changes in pulpmill BOD5 loading. For each site, bars sharing the same letter are not significantly different (P>0.05; Student-Newman-Keul's test); * indicates periods not included in statistical analyses due to insufficient data (n 2) (Chambers et al. 1996).



3.1.2 Wapiti-Smoky River

Sporadic DO data have been collected at two sites on the Wapiti-Smoky river between 1966 and 1992: Wapiti River upstream of Grande Prairie at O'Brien Park, and Smoky River at Bezanson Bridge (20 km downstream of the confluence with the Wapiti River). Comparison of winter (January-March) DO concentrations before and after the 1973 start-up of the Grande Prairie mill showed that concentrations were not significantly different ($P>0.1$) upstream of the mill but were significantly lower ($P<0.01$) in the Smoky River after 1973 (Figure 3.2). Moreover, DO concentrations in the Wapiti-Smoky river did not differ ($P>0.1$) prior to 1973. These results indicate that the Grande Prairie mill has caused a decrease in winter DO concentrations in the Wapiti and Smoky rivers.

3.1.3 Peace and Slave Rivers

Long-term (1977-1988) trends in DO concentrations for the Peace River at Dunvegan were analyzed by Shaw et al. (1990). DO has increased slightly (from approximately 11.9 to 12.2 mg/L; by approximately 0.07 mg/L/y) since 1977 and this trend has been attributed to changes in the water quality of the Williston Reservoir in British Columbia (Shaw et al. 1990).

DO is not routinely measured on the Slave River.

3.2 WINTER WATER QUALITY SURVEYS

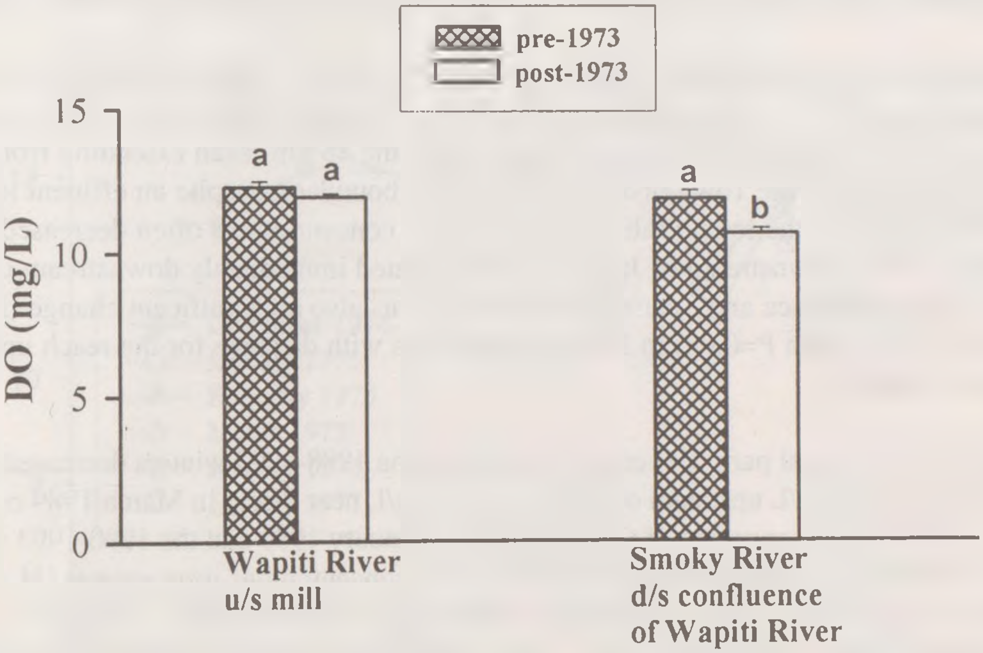
3.2.1 Athabasca River

Surveys of under-ice DO concentrations in the Athabasca River were undertaken by the federal Department of Environment between 1974 to 1977 in Jasper National Park starting approximately 46 (March 1975, 1977) or 57 km upstream of the Town of Jasper and proceeding to approximately 19 km (1977 only) or 36 km downstream of the town. Mid-channel water grabs were collected in duplicate or triplicate from nine sites on 20-22 January and 25-27 February 1975 and 20-21 January 1976, eight sites on 10 December 1974, seven sites on 18-19 March 1975 and three sites on 31 January 1977. Samples were fixed on site and analyzed for DO within 24 h following the azide-Winkler method (Block et al. 1993).

In 1989, Alberta Environment initiated winter water quality surveys of the Athabasca River from upstream of Hinton to Lake Athabasca, a distance of 1243 river kilometres. Surveys were undertaken between 9 January - 15 February 1989, 13 February - 16 March 1989, 14 February - 21 March 1990, 7 February - 14 March 1991, 30 January - 10 March 1992 and 11 February - 16 March 1993. Approximately 70 stations, including mainstem, tributary and effluent ("end-of-pipe") discharges, were sampled in a downstream order at time intervals corresponding to the water time-of-travel as determined by previous dye studies (Noton and Shaw 1989). Two shorter 567 km surveys were also conducted in February and March 1988 from upstream of Hinton to the Town of Athabasca. All samples were analyzed for BOD_5; river and tributary

Figure 3.2 Winter (January-March) dissolved oxygen (DO) concentrations in the Wapiti River upstream of the Weyerhaeuser Canada Ltd. mill and the Smoky River downstream of the

Figure 3.2 Winter (January-March) dissolved oxygen (DO) concentrations in the Wapiti River upstream of the Weyerhaeuser Canada Ltd. mill and the Smoky River downstream of the confluence with the Wapiti River. The two time periods correspond to before and after the opening of the Weyerhaeuser Canada Ltd. mill in 1973. Bars sharing the same letter are not significantly different (P>0.01; ANOVA).



confluence with the Wapiti River. The two time periods correspond to before and after the opening of the Weyerhaeuser Canada Ltd. mill in 1973. Bars sharing the same letter are not significantly different ($P>0.01$; ANOVA).
samples were also analyzed for DO. BOD5 samples were collected in glass bottles, stored at 4oC and analyzed within 24 h at Chemex Labs Alberta Inc. following APHA (1985); DO samples were fixed on site and titrated within 24 h following the azide-Winkler method (APHA 1985). In addition to time-of-travel surveys, continuous DO measurements were taken from approximately January to March 1989 - 1993 at five sites: upstream of Hinton, at Windfall Bridge, upstream of Smith, upstream of Grand Rapids and upstream of Fort McMurray. In addition, four other sites were continuously monitored from January to March 1989: at Obed Coal Bridge, at Ft. Assiniboine, at the Town of Athabasca and downstream of Grand Rapids.

DO concentrations in the headwaters of the Athabasca River (i.e., upstream of the Town of Jasper) ranged from 11.5 to 12.8 mg/L for the 1975-1976 winters (Figure 3.3). There was no significant change ($P > 0.1$) in DO concentrations along the 45 km reach extending from immediately upstream of the Town of Jasper to the park boundary, despite an effluent load to the river of 3948 m3/d from the town (Table 2.1). However, concentrations often decreased approximately 20 km downstream of Jasper at a site located immediately downstream of the confluence of the Athabasca and Snaring rivers. There was also no significant change ($P > 0.3$ except January 1975 when $P=0.08$) in DO concentrations with distance for the reach upstream of the Town of Jasper.

Downstream of the national park, DO concentrations for the 1988-1993 winters decreased from between 11.7 and 12.5 mg/L upstream of Hinton to 5.8 mg/L near Smith in March 1989 or to between 7.1 and 9.5 mg/L upstream of Grand Rapids in January 1989 and the 1990-1993 winters (Figures 3.4 and 3.5). Downstream of Grand Rapids, DO concentrations were greater (11.4 to 12.7 mg/L) than upstream of Hinton but decreased to between 10.0 and 11.2 mg/L over a distance of 394 km. Pulp mill BOD5 loads totalled 3791 kg/d in 1988 when only one mill was operating. With the introduction of a new mill in August 1988, mill BOD5 loading increased to 8999 kg/d in winter 1989 but decreased to 3955 kg/d in winter 1990 due to improved operations at both mills. BOD5 loadings totalled 3203, 3037 and 3133 kg/d during the 1991, 1992 and 1993 winter surveys, respectively, when four mills were operating. Sags in DO were observed below the mill at Hinton for most winters and below the Millar Western Pulp Ltd. mill at Whitecourt during the 1989 start-up winter. In contrast, municipal BOD5 loads were small except for Fort McMurray which discharged an average of 285 kg/d (Table 2.1). Loads for tributaries without effluent discharges ranged from < 1 to 3825 kg/d BOD5, with the Clearwater River (discharging at Fort McMurray) representing the largest tributary load. BOD5 loads were also high for the Lesser Slave River (discharging at Smith); however, recent values are attributable in part to the Slave Lake Pulp Corp. which began operations in December 1990 and discharged 311, 61 and 355 kg/d BOD5 during the 1991, 1992 and 1993 winter surveys, respectively, to the Lesser Slave River 50 km upstream of its confluence with the Athabasca River.

Plots of continuous DO measurements for the winter months from 1989 - 1993 are presented in Noton and Allan (1994) and summarized in Table 3.2. The range in DO concentrations is 10-13 mg/L

Figure 3.3 Dissolved oxygen (DO) concentrations in the Athabasca River for the 93 km reach within Jasper National Park.

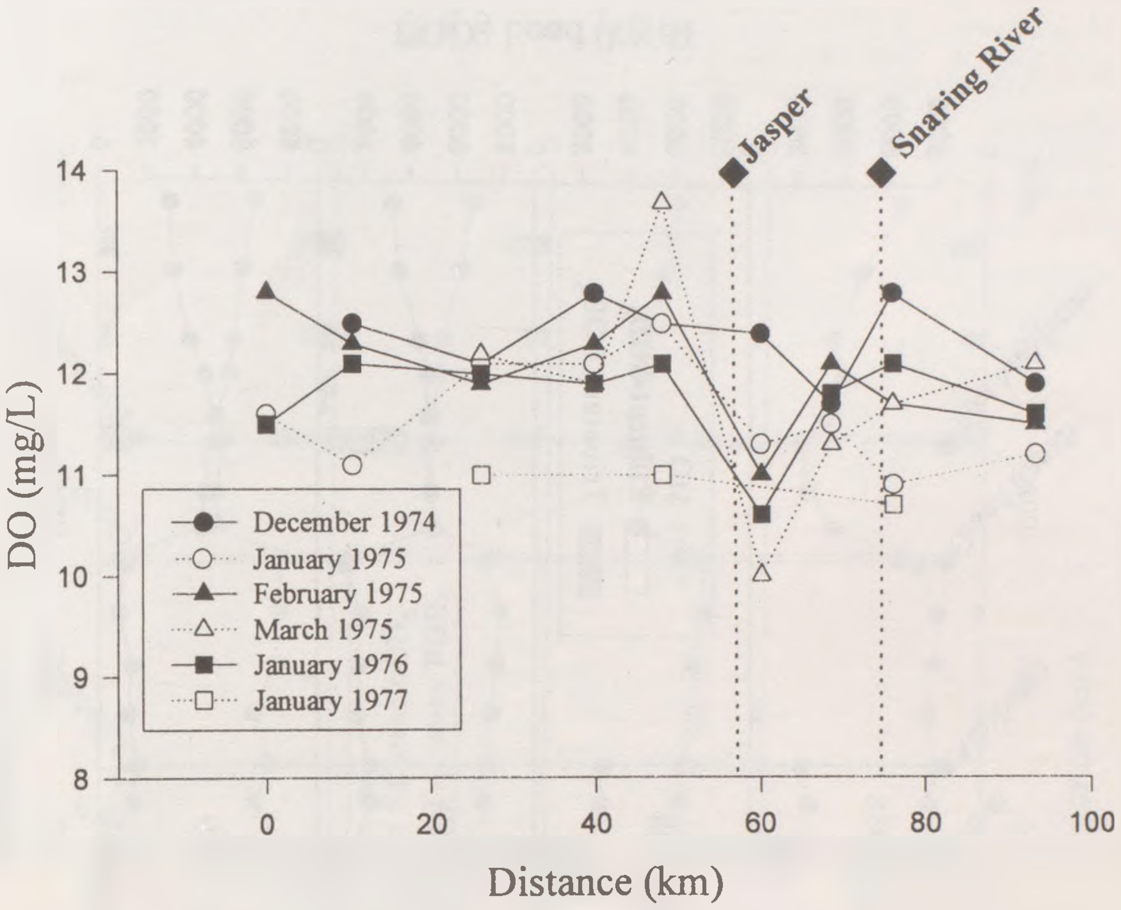


Figure 3.4 BOD5 loads to and dissolved oxygen (DO) concentrations in the Athabasca River from upstream of Hinton to Athabasca for the 1988 winter and to Lake Athabasca for the 1989 winter. Note change in BOD5 scale between Figures 3.4 and 3.5. Data from Noton and Shaw (1989).

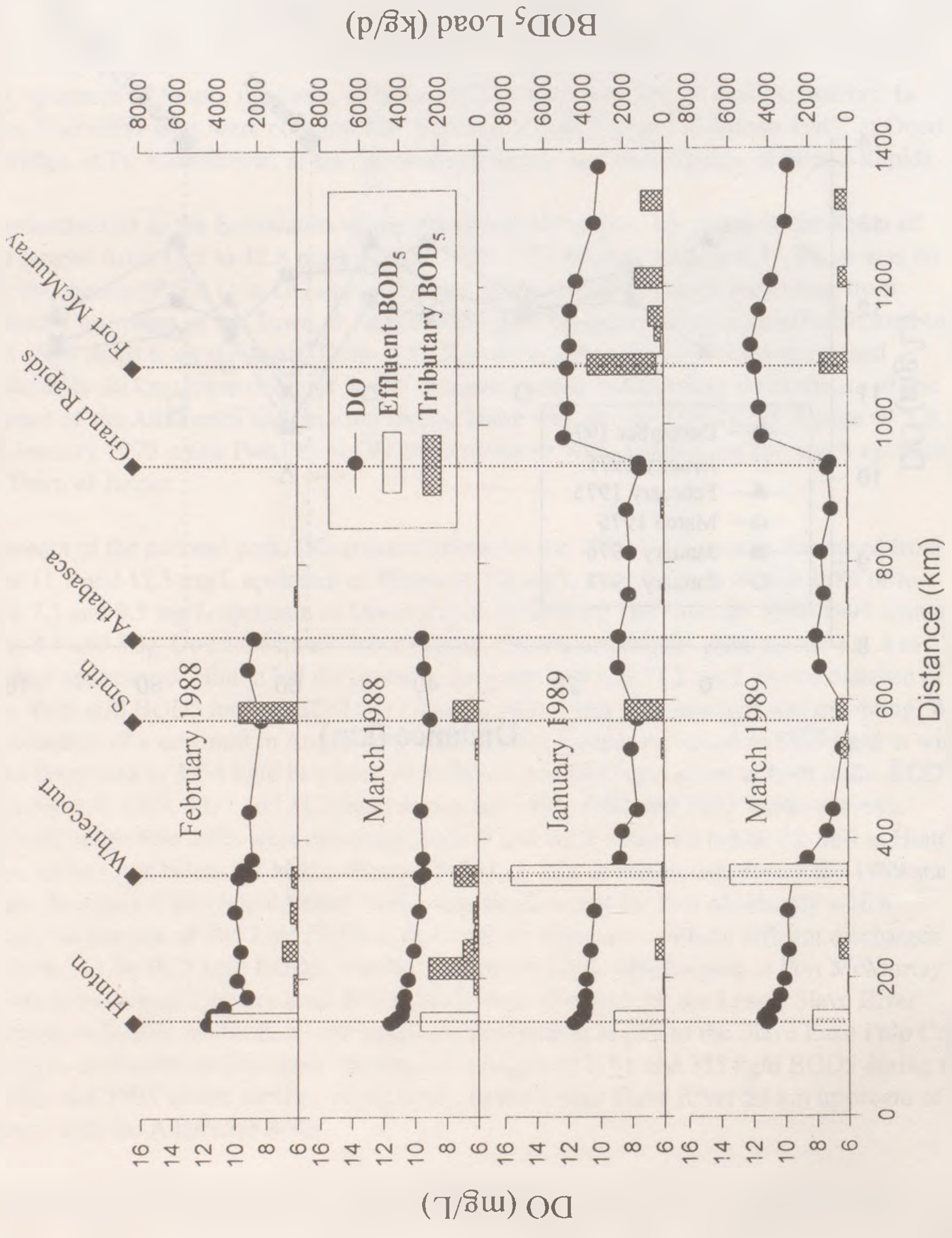


Figure 3.5 BOD5 loads to and dissolved oxygen (DO) concentrations in the Athabasca River from upstream of Hinton to Lake Athabasca for the 1990-1993 winters. Note the change in BOD5 scale between Figures 3.4 and 3.5. Data from Noton and Allan (1994).

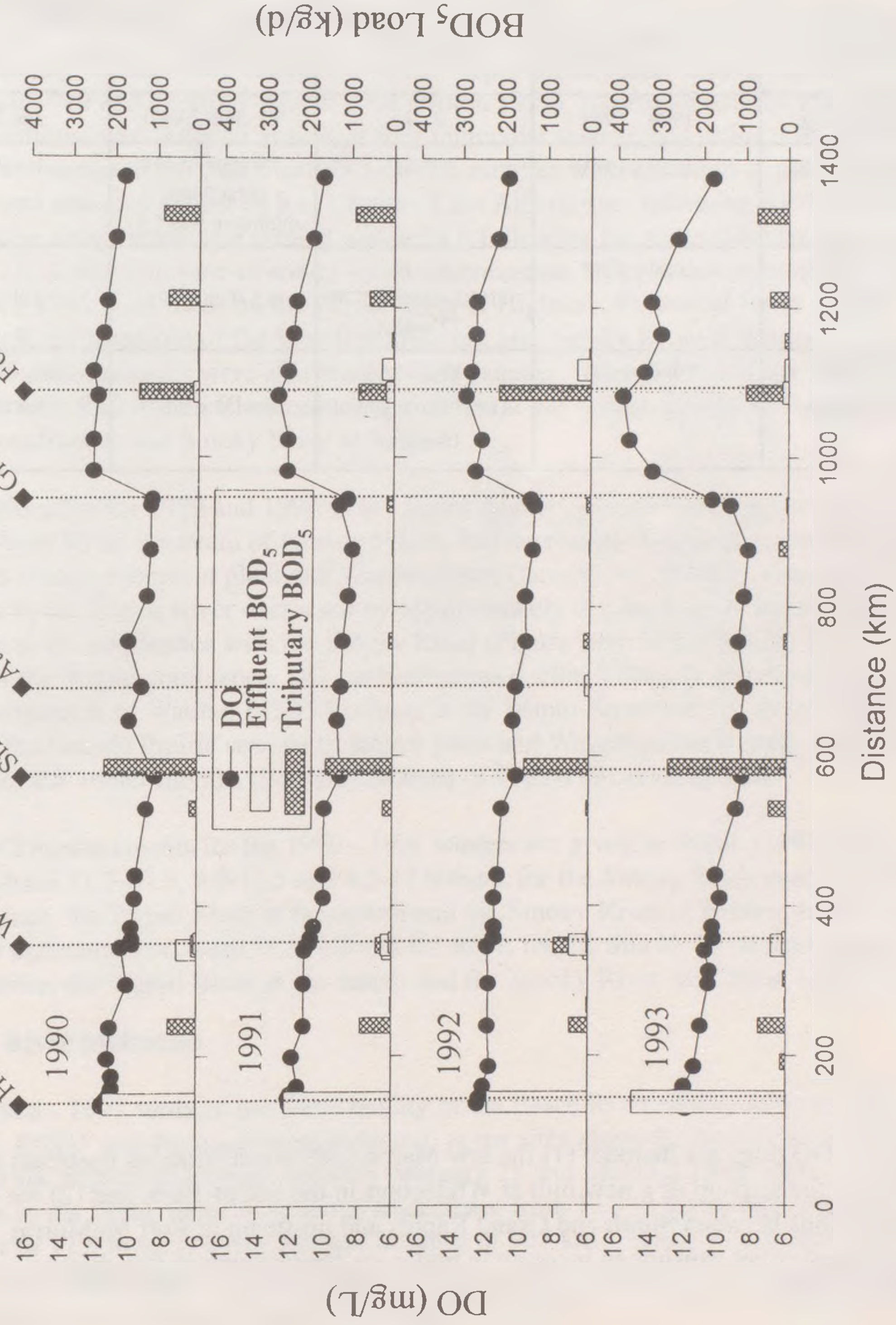


Table 3.2 Summary table of information from continuous dissolved oxygen measurements for the Athabasca River. Dates and concentrations read off graphs in Noton and Allan (1994).

Site	Data Collection Years	Range of Dissolved Oxygen (mg/L)[9]	Minimum Dissolved Oxygen (mg/L)	Range of Dates when Minimum Dissolved Oxygen Occurred
upstream Hinton	1989, 1990, 1991, 1993	9.9 - 13	9.9 (Jan 28/89)	Jan 13 - Feb 5
Windfall Bridge	1989 - 1993	9 - 13	9.1 (Feb 30/89)	Jan 23 - Feb 30
upstream Smith	1989 - 1993	7.9 - 13	7.9 (Jan 30/93) (Mar 23/89 minimum was 5.9)	Jan 23 - Mar 23
upstream Grand Rapids	1989 - 1993	6 - 13 (1993 maximum of 17 mg/L)	6.5 (Feb 6/93)	Feb 4 - Mar 24
upstream Fort McMurray	1989 - 1993	10.4 - 14 (1993 maximum of 16 mg/L)	10.4 (Mar 9/89)	Jan 22 - Mar 21

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[1] Range of DO does not include: (1) the low March 1989 concentrations upstream of Smith because of the start-up of a new mill at Whitecourt in the fall of 1988, and (2) the high 1993 concentrations between Smith and Grand Rapids and upstream of Fort McMurray due to thin ice and snow cover causing an increase in under-ice photosynthesis (for discussion see Noton and Allan (1994).

upstream of Hinton and widens to 6-13 mg/L at Grand Rapids (Table 3.2). In addition, minimum DO concentrations decrease from Hinton to Grand Rapids after which the water is reaerated and concentrations return to levels similar to upstream of Hinton. The dates when minimum DO concentrations were observed shifts from mid-January to early-February upstream of Hinton to early-January to early-March upstream of Grand Rapids.

3.2.2. Wapiti-Smoky River

Winter water quality surveys were conducted on the Wapiti-Smoky river during March 1989, February-March 1990 and February-March 1991 (Noton 1992). Approximately 24 mainstem and tributary stations were sampled as well as four municipal sewage and effluent discharges. All samples were analyzed for BOD5 and DO. BOD5 samples were collected in glass bottles, stored at 4oC and analyzed within 24 h at Chemex Labs Alberta Inc. following APHA (1985); DO samples were fixed on site and titrated within 24 h following the azide-Winkler method (APHA 1985). In addition to time-of-travel surveys, continuous DO measurements from January - March 1990 were taken on the Wapiti River at Highway 40, Wapiti River at the mouth, Smoky River upstream of the Wapiti confluence, and Smoky River at Watino. Continuous DO measurements were also made during January - March 1991 at the Wapiti River upstream of Grande Prairie near Elmworth, Wapiti River at the mouth, Smoky River upstream of the Wapiti confluence and Smoky River at Watino.

DO concentrations for the 1989 and 1990 winter water quality surveys were approximately 12 mg/L in the Wapiti River upstream of Grande Prairie and decreased sharply downstream of the Grande Prairie sewage treatment plant and Weyerhaeuser Canada Ltd. outfalls. Overall, DO concentrations in the Wapiti River decreased by approximately 2-4 mg/L from upstream of Grande Prairie to the confluence with the Smoky River (Figure 3.6). In the Smoky River downstream of the Wapiti confluence, DO concentrations declined linearly to between 7.5 and 10.5 mg/L downstream of Watino. BOD5 loadings to the Wapiti-Smoky River were 87 and 3068 kg/d for the Grande Prairie sewage treatment plant and Weyerhaeuser Canada Ltd., mill respectively, for the winter months (February/March) of 1989-1991 (Figure 3.6).

Continuous DO measurements for the 1990 - 1991 winters are given in Noton (1992) and in general range from 11.5-13.5, 9.0-13.5 and 8.5-12.0 mg/L for the Smoky River upstream of the Wapiti confluence, the Wapiti River at the mouth and the Smoky River at Watino, respectively. Minimum DO concentrations were 11.5, 9.0 and 8.7 mg/L for the Smoky River upstream of the Wapiti confluence, the Wapiti River at the mouth and the Smoky River at Watino, respectively.

3.2.3 Peace River Mainstem

As part of a 1988 - 1991 study of the water quality of the Peace River within Alberta (Shaw et al. 1990), DO, BOD5 and discharge were measured at ten sites along the mainstem and for ten tributaries and six effluent discharges between February 28 and March 2 1989. DO concentrations in the Peace River were found to decrease from 13.7 at the British Columbia - Alberta border to 12.5 mg/L at Peace Point, a distance of 957 km (Figure 3.7). With the exception of the Smoky River, BOD5 loadings were low. Shaw et al. (1990) noted that oxygen depletion is minimal in the Peace River during winter because:

Figure 3.6 BOD5 loads to and dissolved oxygen (DO) concentrations in the Wapiti-Smoky river from upstream of Grande Prairie to downstream of Watino for the 1989-1991 winters. Note DO is not available for 1991 and BOD5 loads are calculated from average BOD5 concentrations for the three years. Data from Noton (1992).

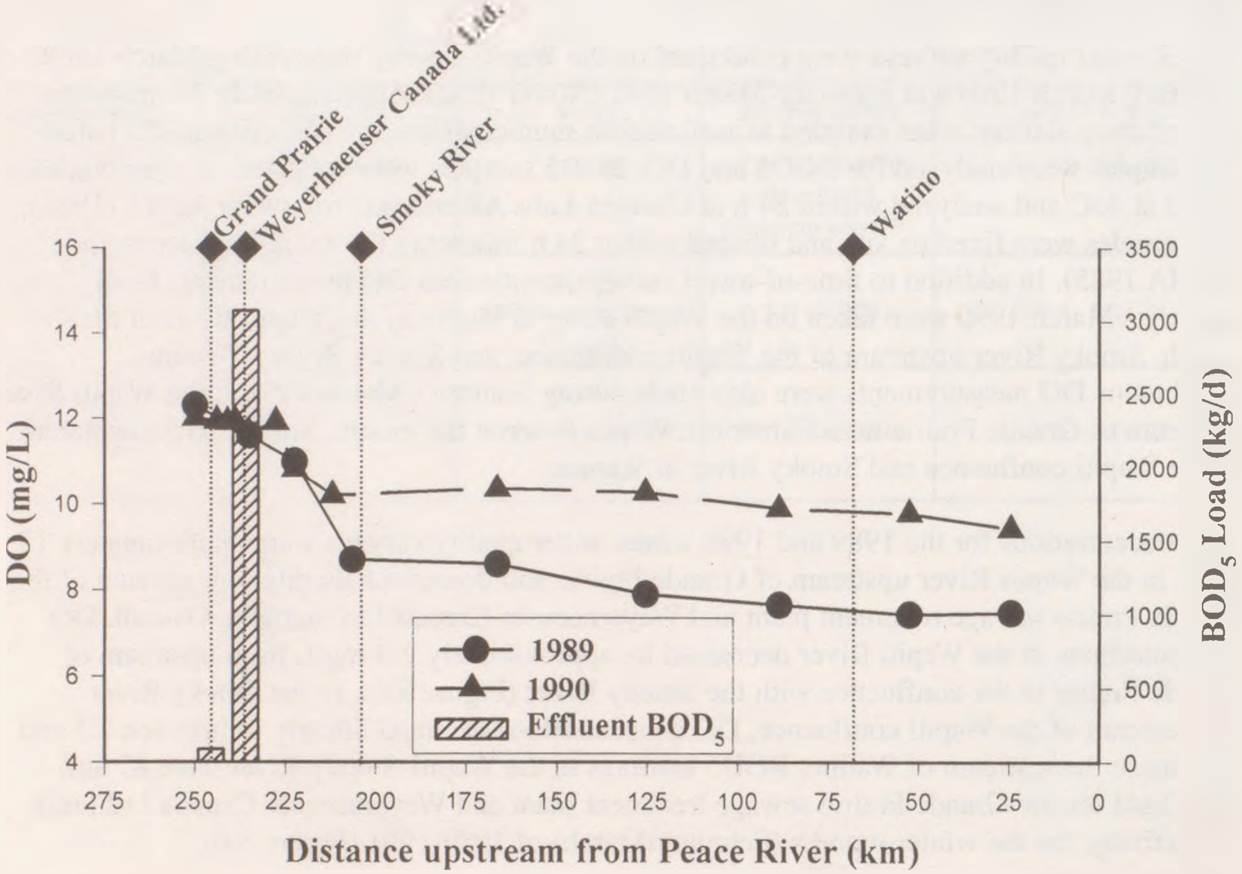
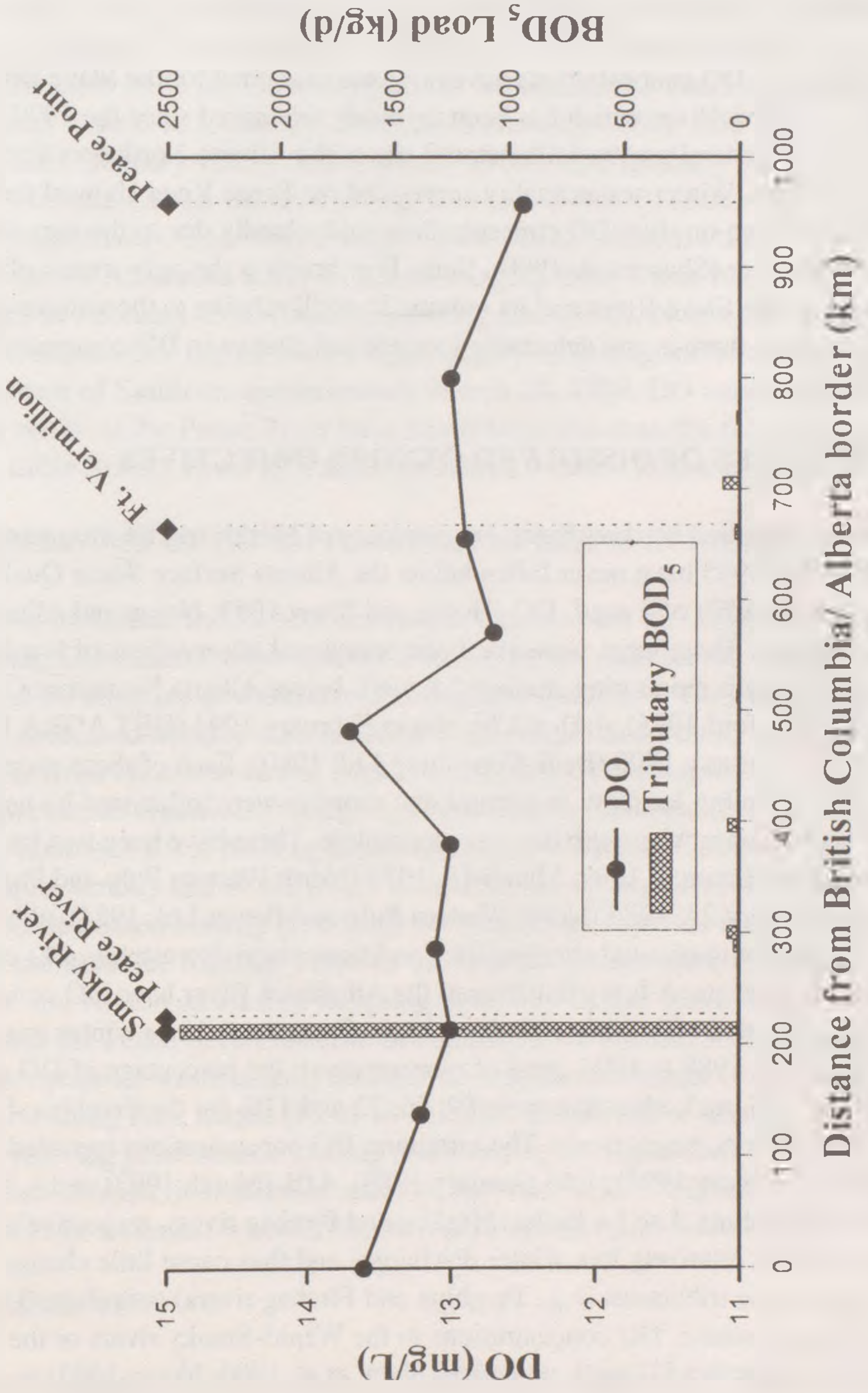


Figure 3.7 BOD5 loads to and dissolved oxygen (DO) concentrations in the Peace River from the British Columbia/Alberta border to the confluence with the Slave River for late winter (February-March) 1989. Data from Shaw et al. (1990).



(1) instream BOD5 concentrations are low, (2) the water column is saturated with oxygen as it enters Alberta, (3) reaeration likely occurs at the Vermilion Chutes and perhaps at the Boyer Rapids, and (4) the reach from the British Columbia border to Peace River remains ice-free for much of the winter.

3.2.4 Slave River

Longitudinal patterns in DO concentrations have not been examined for the Slave River. There is only one site on the Slave River which has been regularly monitored since the 1970's (Slave River at Fitzgerald, the joint federal/provincial/territorial site at the Alberta-Northwest Territories border) but DO is not measured. Winter water quality surveys of the Peace River showed no detectable impact of effluent loading on river DO concentrations undoubtedly due to the very large dilution of the effluent in the river (Shaw et al. 1990). Since Fort Smith is the only source of continuous effluent discharge on the Slave River and its volume is small relative to the volume of the Slave River, it is unlikely that there is any detectable longitudinal change in DO concentrations that is attributable to effluents.

3.3 EXCEEDANCES OF DISSOLVED OXYGEN OBJECTIVES

DO concentrations measured by the Alberta Departments of Health and Environment for the Athabasca River since 1955 have never fallen below the Alberta Surface Water Quality Objective (Alberta Environment 1977) of 5 mg/L DO (Noton and Shaw 1989; Noton and Allan 1994; NRBS historical DO database). There have, however, been occasional observations of low DO on the mainstem during pulp mill monitoring studies: 2.8 mg/L below Alberta Newsprint Co. in February 1995 (Shelast and Brayford 1995), 4.41 at Chisolm in February 1994 (HBT AGRA 1994) and 4.8 mg/L at Windfall in February 1990 (Beak Consulting Ltd. 1990). Each of these exceedances can be attributed to the sampling location: in general, the samples were influenced by near-shore conditions or taken in zones where mixing was incomplete. There have been two low DO values measured upstream of Hinton: 4.10 on March 18, 1976 (North Western Pulp and Power Ltd. 1976) and 3.58 mg/L on January 25, 1984 (North Western Pulp and Power Ltd. 1984), although these low values are likely due to unusual site-specific conditions since downstream DO concentrations were > 8mg/L for both years. A few tributaries to the Athabasca River have DO concentrations less than the 5.0 mg/L objective on a fairly consistent basis. From the Alberta winter water quality surveys conducted from 1988 to 1994 (total of nine surveys), the percentage of DO concentrations that were less than the 5 mg/L objective were 89, 56, 22 and 11% for the Pembina, Lac La Biche, Muskeg and Firebag rivers, respectively. The minimum DO concentrations recorded during these surveys were 0.42 (February 1994), 1.46 (January 1989), 4.01 (March 1993) and 4.52 (March 1993) mg/L for the Pembina, Lac La Biche, Muskeg and Firebag rivers, respectively. While many of these tributaries have relatively low winter discharges and thus cause little change in mainstem DO concentrations, some tributaries (e.g., Pembina and Firebag rivers) contribute 3 to 12 % of the Athabasca discharge in winter. DO concentrations in the Wapiti-Smoky rivers or the Peace River have never been less than the 5.0 mg/L objective (Shaw et al. 1990; Noton 1992).

With respect to the Canadian Water Quality Guideline (CCREM 1987) DO guideline of 6.5

mg/L, concentrations measured by Alberta Environment during their winter water quality surveys were less than this value on the mainstem of the Athabasca River on only one occasion: March 1989 (6.34 and 5.91 mg/L for the Athabasca River upstream of the Pembina River and at Highway #2, respectively). Eight tributaries regularly exceed the 6.5 mg/L guideline. Percent exceedances based on the Alberta Environmental Protection winter water quality surveys are: 89 % for the Pembina River, 86 % for the Lac La Biche River, 86 % for the Firebag River, 57 % for the Muskeg River, 56 % for the McLeod River, 29 % for the Richardson River, 17 % for the Freeman River and 14 % for the Calling River. Minimum DO concentrations for the 1989-1994 survey years were 0.42 (February 1994), 1.46 (January 1989), 4.52 (March 1993), 4.01 (March 1993), 5.28 (January 1989), 5.92 (January 1989), 5.56 (January 1989) and 5.12 (March 1993) for the Pembina, Lac La Biche, Firebag, Muskeg, McLeod, Richardson, Freeman and Calling rivers, respectively. One study conducted for Millar Western Pulp Ltd. measured DO concentrations on the Athabasca River mainstem ranging from 4.8 at Windfall Bridge to 5.9 at Fort Assiniboine in February 1990 (Beak Consulting Ltd. 1990). Noton and Allan (1994) noted low DO concentrations (5.9 mg/L) from a continuously recording meter on the Athabasca mainstem upstream of Smith on approximately March 24, 1989. DO concentrations in the Wapiti-Smoky rivers or the Peace River have never been less than the 6.5 mg/L objective except for the Little Smoky River (5.3 mg/L on March 7 1989) (Shaw et al. 1990; Noton 1992).

3.4 COMPARISONS OF LONGITUDINAL PATTERNS IN DISSOLVED OXYGEN

To compare rates of decline in DO between rivers, Chambers et al. (1996) developed regression equations relating DO concentration to river distance for the Athabasca, Wapiti, Smoky and Peace rivers and 10 other ice-covered rivers throughout the world. They found that DO concentrations decreased linearly with distance in the Wapiti and Smoky rivers and in the Athabasca River from Hinton to Grand Rapids and below Grand Rapids to Lake Athabasca. There was, however, no significant change in DO with river distance ($P=0.8$) for the Peace River and the Athabasca River from upstream of Jasper to Hinton. Comparison of the Athabasca, Wapiti, Smoky and Peace rivers with other ice-covered rivers throughout the world showed that DO decreased linearly ($P < 0.05$) for most (9 of 13) river reaches receiving anthropogenic point-source loading. Three of the four exceptions were the Athabasca River between Jasper and Hinton on all five sampling dates, the Lesser Slave River, Alberta on two of six occasions and the Peace River, Alberta. In contrast, river reaches without point-source loading of anthropogenic waste usually showed no significant change ($P > 0.1$) or an increase ($P < 0.05$) in DO along their length (13 of 18 cases). Comparison of dilution ratios showed that river reaches receiving point-source loading and showing no significant ($P>0.1$) change in DO with distance had effluent:river dilution ratios of less than 0.35%. Significant declines in DO rarely occurred (3 of 34 cases) when effluent:river dilutions ratios were less than 0.35%.

3.5 ASSESSMENT

Discharge of effluent from 15 continuous-discharge point sources (five pulp mills, one oil sands project and nine municipalities, with one mill and one municipality having a combined discharge) along with natural sources of oxygen demand result in a decrease in DO concentrations along the Athabasca River downstream of Hinton to Grand Rapids, with sags in DO occurring below some pulp mill discharges in certain winters. Concentrations return to saturation at Grand Rapids due to reaeration and thereafter decline. DO concentrations remain relatively constant and approach saturation from the headwaters to upstream of Hinton. Historical data from 1958-1995 showed that February-March DO concentrations downstream of Hinton were lowest during the 20-years following the 1957 start-up of the Hinton mill and have since increased significantly ($P < 0.05$) at both Whitecourt and Athabasca. DO concentrations measured by provincial and federal departments for the Athabasca River since 1955 have never fallen below the Alberta Surface Water Quality Objective (Alberta Environment 1977) of 5 mg/L DO (Noton and Shaw 1989; Noton and Allan 1994; NRBS historical DO database). There have, however, been occasional observations of low DO (< 5 mg/L) on the mainstem during pulp mill monitoring studies (Beak Consulting Ltd. 1990; HBT AGRA 1994; Shelast and Brayford 1995) and these have been attributed to the samples being influenced by near-shore conditions or taken in zones where mixing was incomplete. A few tributaries to the Athabasca have DO concentrations less than the 5.0 and 6.5 mg/L objective on a fairly consistent basis: the Pembina, Lac La Biche, Muskeg and Firebag rivers. Comparison of rates of change in DO with distance showed that rates for the Athabasca River were generally less than other ice-covered rivers receiving effluent (Chambers et al. 1996).

In the Wapiti-Smoky rivers, DO concentrations decrease by 2-4 mg/L from upstream of Grande Prairie to the mouth of the Wapiti River and, in the Smoky River, continue to decline by 2-3 mg/L to Watino. Historical data from 1966-1992 indicated that January-March DO concentrations have remained constant upstream of Grande Prairie before and after the 1973 start-up of the Weyerhaeuser Canada Ltd. mill but have decreased significantly in the Smoky River since 1973. DO concentrations in the Wapiti-Smoky river have never fallen below the 5 mg/L Alberta Surface Water Quality Objective (Alberta Environment 1977) (Noton 1992). Comparison of rates of change in DO with distance showed that rates for the Wapiti River were high compared to other ice-covered rivers (Chambers et al.1996); however, DO concentrations are never as low as in the Athabasca River because the Wapiti River is comparatively short (i.e., 44 km from Grande Prairie to the Smoky River) and then convergences with the much larger Smoky River.

Oxygen depletion is minimal in the mainstem of the Peace River during winter due to low instream BOD5 concentrations, reaeration at Vermillion Chutes and perhaps Boyer Rapids, and the fact that the water column is saturated with oxygen as it enters Alberta and the reach from the British Columbia border to Peace River remains ice-free for much of the winter (Shaw et al. 1990). While longitudinal data on DO concentrations in the Slave River are not available, it is unlikely that there is any appreciable decline in DO concentrations with distance. The 5 mg/L Alberta Surface Water Quality Objective (Alberta Environment 1977) has never been exceeded on the Peace River (Shaw et al. 1990).

CHAPTER 4.0
DISSOLVED OXYGEN MODELLING

4.0 DISSOLVED OXYGEN MODELLING

In addition to water quality monitoring, recent studies of DO in the Athabasca River have expanded to include simulation modelling of DO dynamics. Water quality models are important tools for estimating the impact of nutrient, contaminant and BOD loadings on water and sediment chemistry, and biota in rivers. Often these models represent the best information available to decision makers in assessing the effects of existing and future loading scenarios. Previous efforts to model DO in the Athabasca River included: (1) an initial attempt using the model WQRRS (Water Quality for River and Reservoir Systems) (Charles Howard and Associates 1984), (2) an initial assessment of the model DOSTOC for use on the Athabasca River (Hamilton et al. 1988), (3) calibration of DOSTOC to winter 1988 and 1989 data (Macdonald and Hamilton 1989), and (4) verification of the 1989 calibration using winter 1990 data (Macdonald and Radermacher 1992). As part of the NRBS, the validity of the 1989 calibration was further tested using winter 1991 and 1992 data (Macdonald and Radermacher 1993). In March 1993, a workshop was organized by the NRBS to review and assess available modelling approaches for estimating the impact of BOD and nutrient loadings on the water quality of the Peace and Athabasca river systems (Culp and Chambers 1994). As a follow up to this workshop, input parameters for DOSTOC were tested and validated for their applicability to the Athabasca River (Chambers et al. 1996). In addition, Alberta Forestry Products Association in collaboration with Alberta Environmental Protection recently implemented WASP to address temporal variations in DO (Golder Associates Ltd. 1995).

The aim of this chapter is to review DO water quality modelling in relation to conditions in the Athabasca River during the 1988-1993 winters (under-ice periods) as modelled by steady state (DOSTOC) and dynamic (WASP) models.

4.1 DO WATER QUALITY MODELS

“Modelling is done to aid the conceptualization and measurement of complex systems, and, sometimes, to predict the consequences of an action that would be expensive, difficult, or destructive to do with the real system” (Hall and Day 1977). Models in general may be of two types: mechanistic (based on theoretical, often simplified understanding of processes) and empirical (based on a statistical summary of data) (Reckhow 1994). There are many models currently accessible but the difficulty is deciding which model meets the study objectives. Some considerations of model selection are: type of water body (lake, river, reservoir), time variability (do any of the variables change over time?), constituents modelled (are all the variables of interest included in the model, i.e. are all the DO components of interest included in Fig. 1.1?), model input and calibration data (are these available or do additional data need to be collected) and cost (e.g., model purchase and implementation, data acquisition) (Linton and Hamilton 1988). The value of modelling over monitoring studies is that cause and effect relationships may be defined and predictions may be made (Chapter 1).

Compared to efforts directed at modelling river-water DO during the open-water season , there has been little modelling of DO in ice-covered rivers. For the few ice-covered rivers which have been modeled, the Streeter-Phelps (1925) equations (or modifications thereof) have been employed to explain the relationship between BOD and DO. The Streeter-Phelps DO-BOD equations are a set simple differential equations based on self-purification of a system by chemical reactions between pollutants and DO (Stehfest 1978). Ranjie and Huimin (1987) used these equations to describe the under-ice DO deficit in the Tu Mein River, China and attributed the deficit to limited reaeration (due to ice cover) and high BOD load (due to low decomposition caused by cold temperatures and low dilution of point-source pollutants). Brekhovskikh and Volpian's (1991) modelling of the Sukhona River, Russia attributed the DO deficit to the addition of wood debris from pulp and paper mills which caused a zone of oxygen deficit, the low intensity of photosynthesis and the long period of ice cover.

Efforts to model DO in the rivers of the Northern Rivers have largely used the deterministic DO simulation model DOSTOC (Dissolved Oxygen STOChastic model) (Hamilton et al. 1988; Macdonald and Hamilton 1989; Macdonald and Radermacher 1992, 1993; Chambers et al. 1996). The model was developed in 1987 for the Planning Division of Alberta Environment and has been described in detail by HydroQual Consultants Inc. and Gore & Storrie Ltd. (1987) and Zielinski (1988). DOSTOC is a steady-state, one-dimensional model based on the system of ordinary differential equations developed by Streeter and Phelps (1925). Their original equations were modified to include the major sources and sinks of oxygen in river processe, including atmospheric reaeration, consumption of DO as a result of the conversion of NH4+ to NO3 (nitrogenous oxygen demand, NOD), consumption of DO by degradation of organic material (biochemical oxygen demand, BOD), production/consumption of DO as a result of plant photosynthesis and respiration, and consumption of DO at the streambed by benthic organisms and chemical processes (SOD). In the stochastic version of DOSTOC, all rates as well as respiration, photosynthesis and diffuse source loadings are regarded as stochastic processes and initial conditions upstream in the river and tributaries are regarded as random variables (Zielinski 1994). One of the weakness of DOSTOC is that all dynamic phenomena are neglected (Zielinski 1994).

In 1994, the dynamic water quality simulation model WASP (Water Quality Analysis Simulation Program) was implemented by Golder Associates Ltd. (1995) for Alberta Forestry Products Association and Alberta Environmental Protection. The need to move from a steady-state model like DOSTOC to a dynamic model such as WASP was identified because of the concern that SOD and DO at any site vary over the winter (Golder Associates 1995). WASP was developed in 1981 by the United States Environmental Protection Agency (Di Toro et al. 1981). Its structure and application to northern river modelling has been described by Macdonald and Shaw (1994). WASP is a generalized framework for water quality modelling which allows greater flexibility than a steady-state model with respect to dimensions (one, two and three, i.e. time, distance and cross-channel variability), time-variable exchange coefficients, advective flows, waste loads, water quality boundaries and kinetic processes (Macdonald and Shaw 1994). DO is modelled within WASP using the eutrophication model, EUTRO, which is composed of five state variables: algal carbon, ammonia, nitrate, chemical-BOD and DO. EUTRO involves solving the Streeter-Phelps BOD-DO equations also used in DOSTOC, with the sources of DO being reaeration and input by tributary and headwaters and the sinks being BOD decay (sediment and water) and tributary inflow of low oxygen water.

4.2 DOSTOC MODELLING

As part of the NRBS, simulation modelling of DO in the Athabasca River during winter was undertaken by Macdonald and Radermacher (1993) and Chambers et al. (1996). Prior to the NRBS, DOSTOC had been calibrated for the Athabasca River using 1988-1989 data (Hamilton et al. 1988; Macdonald and Hamilton 1989) and validated with 1990 data (Macdonald and Radermacher 1992). Calibration is defined as the process of assigning discrete measurements to the dependent variable in order to estimate values for model constants or parameters (Beck and Arnold 1977). In the case of the Athabasca River, calibration entailed the use of measured values for DO, BOD5, discharge, time of travel and reaeration while BOD settling and SOD were set to give the best match between observed and predicted DO concentrations. To validate these estimates of BOD settling and SOD, Macdonald and Radermacher (1993) ran DOSTOC for the 1991 and 1992 winters using the calibration approach from 1989. They found, in general, that the calibration variables developed for the 1988-1989 winters gave predictions of DO concentrations within 0.5 mg/L for the 1991 and 1992 winters but in specific reaches DO was over or under predicted by up to 1.0 mg/L.

To address concerns about model calibration (specifically the practice of assigning values to parameters for which little or no data are available), Chambers et al. (1996) established values for most of the processes that consume or add oxygen to the Athabasca River between Hinton and Grand Rapids and then used DOSTOC to test the ability of the improved database to predict DO concentrations in the Athabasca River during winter. These model runs were not calibrated. Only measured values were used for the rate processes which affect river DO concentrations, and the quantity and variability of BOD loading from headwater, tributary and point sources (Table 4.1). (Information on the frequency and approach for measuring these parameters is given in Chambers et al. (1996)). The only exceptions were temperature correction factors from HydroQual Consultants Inc. and Gore & Storrie Ltd. (1987) which were used to adjust the BOD decay rates for pulp mills, STP's and tributaries from the laboratory measured values at 200C to the field conditions of 00C. Chambers et al. (1996) found that for 1988 to 1993, correlation coefficients relating predicted and observed DO concentrations varied from 0.51 in February 1988 to 0.92 in 1991 (Table 4.2; Figure 4.1). In 1990 and 1991, the observed DO values were all within the 90% confidence limits set by the stochastic analysis. For January 1989, 1992 and 1993 the model simulations were a reasonable fit to the observed data with 17 of 23, 18 of 19 and 17 of 20 observed DO values, respectively, within the 90% confidence limits. DO concentrations for February 1988, March 1988 and March 1989 and 1994 were not well simulated, with only 12 of 16, 11 of 14, 12 of 22 and 13 of 21 observed DO values, respectively, falling inside the 90% confidence limits. The best model fits (r2 = 0.89 and 0.92) were obtained for the years 1990 and 1991. While the model predicted sharp changes in DO in response to the Whitecourt mill and STP effluent inputs and certain tributary inputs (e.g., the Pembina and Lesser Slave rivers) and a more gradual sag in response to the Hinton combined effluent (Figure 4.1), discrepancies between predicted and observed DO were still observed in the sag zones immediately below mill discharges. Here DO concentrations were generally over-predicted, possibly due to the lack of information on NOD to allow inclusion of this factor in the modelling. The model results were surprisingly good since no calibration was performed on the model: all input measurements and rates were laboratory or in situ measurements for the Athabasca River and its tributaries, industries and STP's with the exception of the temperature correction factors. The model results indicated that reasonable simulation could be expected for the

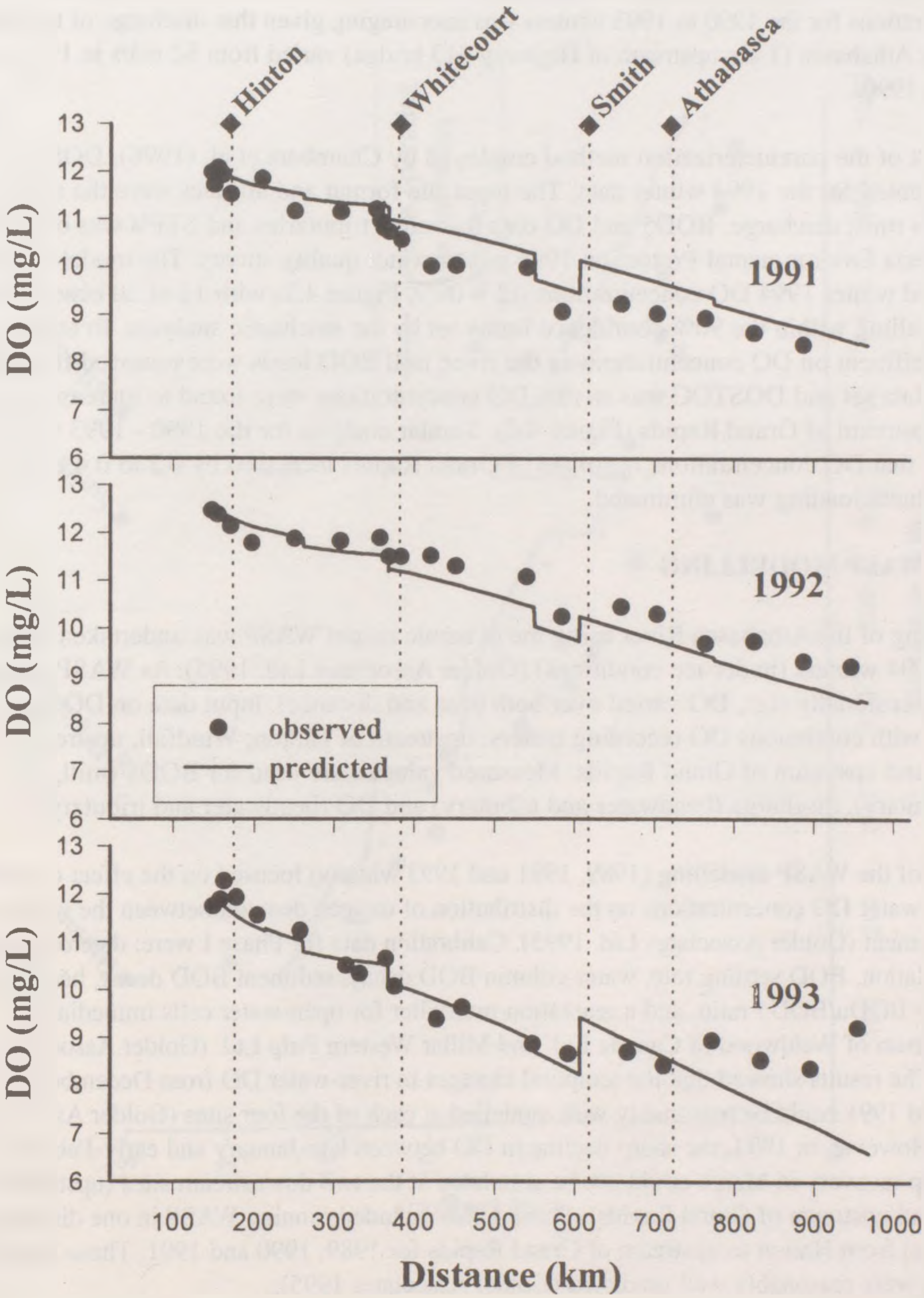
Table 4.1 Summary table of sources of data for DOSTOC runs. Further information on on the frequency and approach for measuring these parameters is given in Chambers et al. (1996).

Parameter	**Source of Data**
Atmospheric reaeration	0.001 day-1 for ice-covered reaches; 0.911 day^{-1} at reference temperature of 20 C and reference flow of 50 m^3/s (after Macdonald *et al.* 1989).
BOD decay rate	Mean annual decay rates for mill effluent obtained from each pulp mill. Decay rates set to 0.026 day^{-1} for sewage effluent and 0.026 day^{-1} for tributaries and headwater.
BOD Sedimentation sedimentation rate	was calculated using Krishappan *et al.* (1995) transport rates from belowHinton. In the absence of data for settling rate below other mills on the Athabasca River, the Hinton values were applied to all other mills.
BOD_5	Industrial, sewage, headwater and tributary data (expressed as mg/L) collected during the Alberta Environment winter water quality surveys.
$BOD_u:BOD_5$	Mill effluent ratios obtained from the pulp mills. Ratio set to 7.80 for sewage and to 8.03 for tributaries and headwater at reference temperature of 20 C.
Diffuse loading	No data; set to 0 tonnes/km/day.
DO	Collected during the Alberta Environment winter water quality surveys (expressed as mg/L).
Nitrogenous oxygen demand (NOD)	No data; set to 0 mg/L/day.
Effluent discharge	Obtained from the industries and the sewage facilities (expressed as m^3/s).
River discharge	Obtained from Technical Services Division, Alberta Environment and Water Survey of Canada (expressed as m^3/s).
Sediment oxygen demand (SOD)	SOD ($g/m^2/d$) was measured *in situ* during the 1989, 1990, 1992 , 1993, 1994, and 1995 winters (Casey and Noton 1989; Casey 1990; Monenco Inc. 1992; HBT AGRA Ltd. 1993a, b; HBT Agra Ltd. 1994; Noton 1995). Mean SOD ($g/m^2/d$) from these years were plotted and values read from the graph at the mid-point of each modelled reach. Areal SOD ($g/m^2/d$) was converted to volumetric SOD (mg/L/d) by multiplying by average water depth. Since SOD was measured *in situ* at 0^0C all values were temperature corrected to 20^0C to fit the model requirements and then back corrected during model runs to 0^0C.
Time of travel	The Athabasca River was divided into nine hydraulic reaches (Macdonald and Hamilton 1989) and Leopold-Maddock coefficients were derived for each reach from HEC-2 simulations using under-ice time-of-travel and river cross-sections measured by Andres *et al.* (1989) and Haufe and Coome (1980). The Leopold-Maddock coefficients were then used to estimate reach-average travel time (days) and reach average depth (m).

Table 4.2 Statistical results of model simulations undertaken by Chambers et al. (1996). (r2 is the coefficient of determination; N/A means data are not available). The coefficient of determination or the Nash-Sutcliffe coefficient is a goodness of fit criteria recommended by the ASCE Task Committee on Definition of Criteria for Evaluation of Watershed Models (ASCE 1993) for continuous hydrograph modelling.

Year	**r^2 value**	
	Chambers *et al.* (1996)	**After Macdonald and Hamilton (1989) and Macdonald and Radermacher (1992)**
Jan 1988	0.51	0.85
Mar 1988	0.53	0.64
Jan 1989	0.79	0.91
Mar 1989	0.56	0.91
1990	0.89	0.76
1991	0.92	N/A
1992	0.74	N/A
1993	0.81	N/A
1994	0.78	N/A

Figure 4.1 Dissolved oxygen (DO) concentrations for the Athabasca River, AB showing predicted (with the simulation model DOSTOC) and observed values for recent winters (February/March):1991, 1992 and 1993 (Chambers et al. 1996).



reach between Hinton and Grand Rapids for the more recent years (1990 - 1993). Poorer predictions in early years (1988 and March 1989) may have related to the limited data on tributary and STP inputs and mainstem DO concentrations for 1988 and, in March 1989, to the large and erratic BOD loadings from Millar Western Pulp Ltd. which had likely not equilibrated with instream processes. The fact that the model was reasonably successful at predicting DO concentrations for the 1990 to 1993 winters was encouraging given that discharge of the Athabasca River at Athabasca (1 km upstream of Highway 813 bridge) varied from 62 m3/s in 1993 to 117 m3/s in 1990.

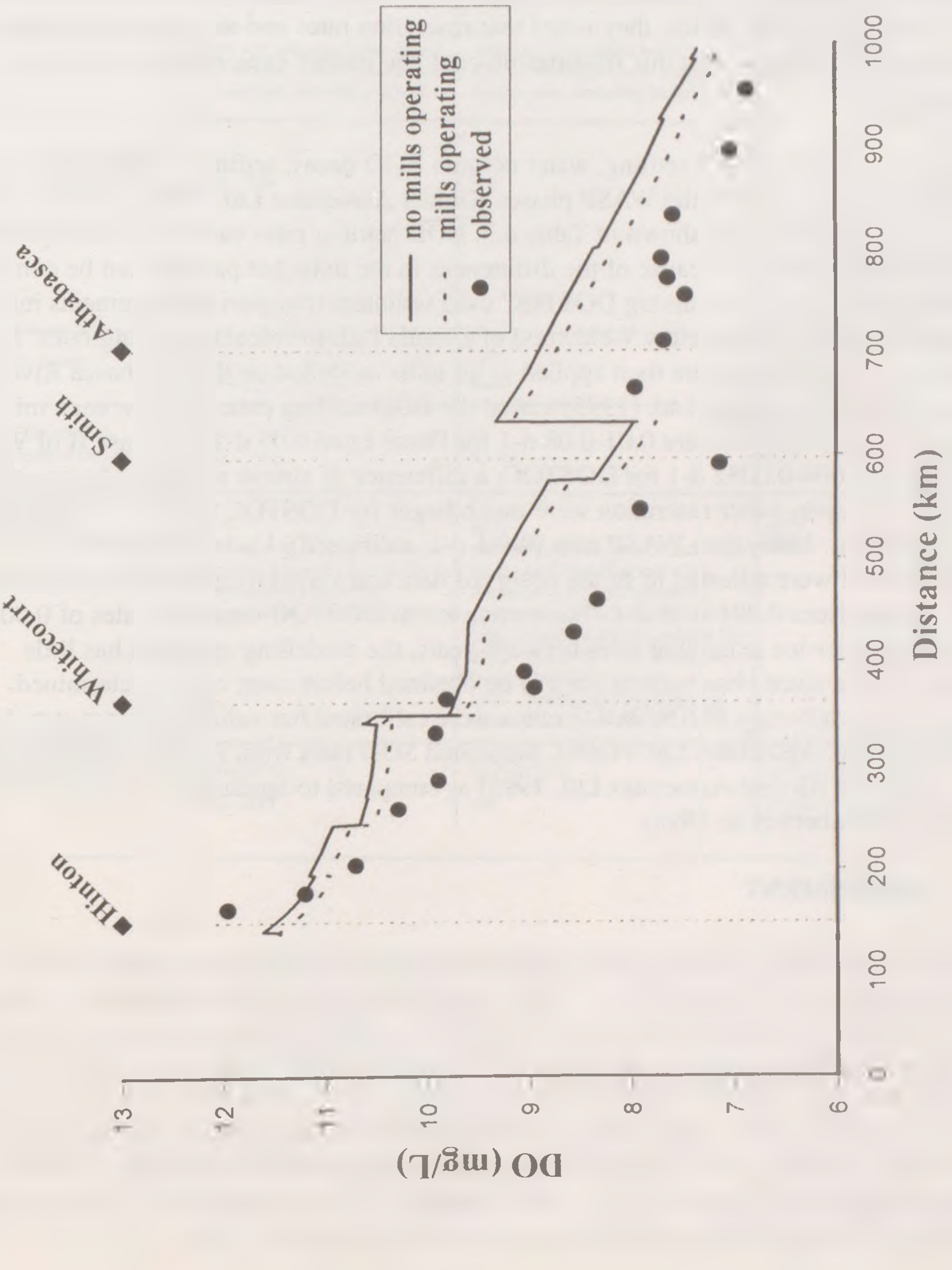
As a test of the parameterization method employed by Chambers et al. (1996), DOSTOC was implemented for the 1994 winter data. The input file format and all rates were the same as previous runs; discharge, BOD5 and DO data for mills, tributaries and STP's was obtained from the Alberta Environmental Protection 1994 winter water quality survey. The model successfully predicted winter 1994 DO concentrations (r2 = 0.79, Figure 4.2) with 12 of 20 observed DO values falling within the 90% confidence limits set by the stochastic analysis. To test the impact of mill effluent on DO concentrations in the river, mill BOD loads were removed from the 1994 winter data set and DOSTOC was re-run. DO concentrations were found to increase by 0.2 mg/L upstream of Grand Rapids (Figure 4.2). Similar analysis for the 1990 - 1993 winters showed that DO concentrations upstream of Grand Rapids increased by 0.2 to 0.4 mg/L when mill effluent loading was eliminated.

4.3 WASP MODELLING

Modelling of the Athabasca River using the dynamic model WASP was undertaken for the 1989-1994 winters (under-ice conditions) (Golder Associates Ltd. 1995). As WASP was run two-dimensionally (i.e., DO varied over both time and distance), input data on DO were limited to sites with continuous DO recording meters: upstream of Hinton, Windfall, upstream of Smith, and upstream of Grand Rapids. Measured values were used for BOD5 (mill, headwater and tributary), discharge (headwater and tributary) and DO (headwater and tributary).

Phase I of the WASP modelling (1989, 1991 and 1993 winters) focused on the effect of variations in river-water DO concentrations on the distribution of oxygen demand between the water column and sediment (Golder Associates Ltd. 1995). Calibration data for Phase I were: date of initial BOD accumulation, BOD settling rate, water-column BOD decay, sediment BOD decay, headwater and tributary BODu/BOD5 ratio, and a reaeration multiplier for open-water cells immediately downstream of Weldwood of Canada Ltd. and Millar Western Pulp Ltd. (Golder Associates Ltd. 1995). The results showed that the temporal changes in river-water DO from December - March 1989 and 1991 could be reasonably well modelled at each of the four sites (Golder Associates Ltd. 1995). However, in 1993, the sharp decline in DO between late-January and early-February and the sharp recovery in March could not be simulated at the two downstream sites (upstream of Smith and upstream of Grand Rapids). Phase I also included running WASP in one dimension (distance) from Hinton to upstream of Grand Rapids for 1989, 1990 and 1991. These longitudinal changes were reasonably well predicted (Golder Associates 1995).

Figure 4.2 Dissolved oxygen (DO) concentrations for the Athabasca River, AB showing predicted (with and without mill BOD5 loads using the simulation model DOSTOC) and observed values for the 1994 winter (February/March).



To address the problems identified with the 1993 model runs, Golder Associates Ltd. (1995) undertook Phase II (1991, 1992, 1993 and 1994 winters) of the WASP modelling exercise and focused on the effect of temporally-varying reaeration rates. Open-water reaeration rates were calculated on the basis of hydraulic conditions using the O'Connor-Dobbins formula and then adjusted within EUTRO to reflect changing ice conditions (Table 4.3). Each year was adjusted independently to match the predicted and observed DO concentrations (Table 4.3). While the approach of adjusting the reaeration rate based upon measured DO values does not allow predictions of future scenarios, they noted that reaeration rates and air temperature may be correlated and suggested that this relationship could be further explored for future use in predicting DO.

Calibration values for BOD settling, water column BOD decay, sediment BOD decay and reaeration rates for each of the WASP phases (Golder Associates Ltd. 1995) and from DOSTOC (Chambers et al. 1996) are shown in Table 4.3. BOD settling rates cannot be directly compared between the two models because of the differences in the units but patterns can be compared. Chambers et al. (1996) in running DOSTOC used sediment transport measurements made by Krishnappan et al. (1995) below Weldwood of Canada Ltd. to calculate settling rates. For lack of other data, these rates were then applied to all mills modelled on the Athabasca River. In contrast, Golder Associates Ltd. (1995) varied the BOD settling pattern below each mill. Water column BOD decay rates were 0.01-0.08 d-1 for Phase I and 0.05 d-1 for Phase II of WASP compared to 0.004-0.0082 d-1 for DOSTOC, a difference of almost an order of magnitude. As well, rates for open-water reaeration were much larger for DOSTOC (0.74 d-1; measured by Macdonald et al. 1989) than WASP runs (0-0.1 d-1; calibrated). Under-ice reaeration rates for WASP Phase II were adjusted to fit the observed data and varied over the year and between years, ranging from 0.001-0.05 d-1. These compare to DOSTOC measured rates of 0.0008 d-1. By varying under-ice reaeration rates between years, the modelling approach has little predictive value since observations need to be obtained before rates can be determined. Headwater and tributary BODu/BOD5 ratios were calibrated but values were not stated in the report by Golder Associates Ltd. (1995). Simulated SOD rates from Phase I ranged from 0.08 to 0.17 g O2/m2/d (Golder Associates Ltd. 1995) as compared to measured rates of 0.02 to 0.31 g O2/m2/d (Chambers et al. 1996).

4.4 ASSESSMENT

Chambers et al. (1996) validated input parameters for use in simulation modelling of DO concentrations in the Athabasca River. They found that when the deterministic DO simulation model DOSTOC was implemented using only in situ or laboratory measurements for all input parameters (with the exception of temperature correction coefficients), reasonable fits to the observed data (i.e., r2 0.74) were obtained for January 1989 and the 1990-1993 winters with 70% of the observed DO values falling inside the 90% confidence limits. The fact that the model was reasonably successful at predicting DO concentrations for the 1990 to 1993 winters was encouraging given that discharge of the Athabasca River at Athabasca (1 km upstream of Highway 813 bridge) varied from 62 m3/s in 1993 to 117 m3/s in 1990.

Table 4.3 Comparison of DOSTOC and WASP rates. DOSTOC rates from Chambers et al. (1996) and WASP rates from Golder Associates Ltd. (1995). All rates are at 0oC. N/S indicates rates not stated. N/A indicates not applicable. Note differences in BOD settling units.

Parameter	WASP - Phase 1	WASP - Phase 2	DOSTOC
BOD settling	(m/d) same rate immediately below each mill and then varied with distance downstream, depending on mill	(m/d) same rate immediately below each mill and then varied with distance downstream, depending on mill	(d^{-1}) same settling pattern independent of mill type
Water-column BOD decay	(d^{-1}) 0.01 - 0.08	(d^{-1}) 0.05	(d^{-1}) all tributaries and headwaters 0.0061; d/s Weldwood of Canada Ltd. 0.0082; d/s Alberta Newsprint Co. 0.0066; d/s Millar Western Pulp Ltd. 0.0040; all d/s sewage treatment plants 0.0061; and Lesser Slave River 0.0052
Sediment BOD Decay	(d^{-1}) 0.005-0.08	(d^{-1}) 0.001	N/A
Weldwood of Canada Ltd. and Millar Western Pulp Ltd. open-water reaeration rate	(d^{-1}) N/S	(d^{-1}) 0 - 0.1	(d^{-1}) 0.74
under-ice reaeration	(d^{-1}) constant over time but variable for each simulation (0 - 0.1) for d/s of Weldwood of Canada Ltd. and d/s Millar Western Pulp Ltd.	($d^{\ 1}$) variable over time for each simulation all years - 0.04-0.05 through Dec. decreased to 0.01 throughout Jan 1991 - remained at 0.01 until mid-Mar 1992 - remained at 0.01 until mid-Feb 1993 - reduced to 0.001 in mid-Feb, increased to 0.02 end-Feb 1994 - reduced to 0.001 in Feb and remained until mid-Mar	(d^{-1}) 0.0008
SOD (d/s Weldwood of Canada Ltd.)	(g O_2/m^2/d) 0.08 - 0.17	(g O_2/m^2/d) N/S	(g O_2/m^2/d) 0.018 - 0.31

DO simulation modelling undertaken with the dynamic model WASP by Golder Associates Ltd. (1995) for Alberta Forestry Products Association and Alberta Environmental Protection showed that temporal changes in river-water DO concentrations could not be modelled without adjusting open-water reaeration rates each year so as to match the predicted and the observed DO concentrations. In addition, BOD settling, water-column BOD decay, sediment BOD decay and reaeration rates also differed (often by an order of magnitude) between those calibrated in the WASP modelling (Golder Associates Ltd. 1995) and the measured values used in the DOSTOC modelling (Chambers et al. 1996).

The concurrent DO modelling of the Athabasca River by two groups using different approaches highlights the need to clearly define modelling goals and validate assumptions made during the modelling process. There appear to be two goals with respect to DO modelling in the Northern River basins: (1) short-term compliance assessments (i.e., predicting DO levels during the upcoming winter), and (2) long-term basin management (i.e., to establish license requirements with respect to changing industrial operations). Dynamic models (i.e., allowing for temporal and downstream variability in DO) may be better suited for addressing the short-term goal because early DO winter data could be used in predicting DO concentrations during late winter. Modelling for long-term basin management focuses on average or low-flow conditions and, hence, could be accomplished using a deterministic approach. For both approaches, a probabilistic model should be employed so as to allow assessment of the effect of variances in model input parameters on the confidence of the model predictions. However, before proceeding with additional modelling, basic issues such as validating the ice-cover Leopold-Maddock coefficients used in calculating reach velocities (for details see Chambers et al. 1996) need to be resolved before more complex modelling is attempted.

CHAPTER 5.0

DISSOLVED OXYGEN REQUIREMENTS OF FISH

5.0 DISSOLVED OXYGEN REQUIREMENTS OF FISH

5.1 INTRODUCTION

Studies into the DO requirements of fishes were prompted by the Northern River Basins Study Board Question number 7: "What concentrations of dissolved oxygen are required seasonally to protect the various life stages of fish, and what factors control dissolved oxygen in the rivers?" The question arises from our knowledge that winter DO levels, especially during ice-cover and low light (photosynthesis) conditions, may limit over-winter survival of fishes, their developing eggs or their larval young. The question is closely related to the issue of reduction of winter DO resulting from the addition of oxygen-depleting materials to the rivers by industrial and municipal effluents, and natural processes. While acute effects of lowered DO on fishes are likely avoided by most industrial and municipal licensing conditions, the long-term population and ecosystem health effects are of equal concern and less well understood. Most public comments arising out of the NRBS Traditional Knowledge and Other Uses surveys of northern river basins residents suggest a strong perception that industrial development in the basins has already begun to result in chronic effects on fish (Bill and Flett 1996; Thompson and MacLock 1996).

The first project commissioned by the NRBS in relation to fish and DO was a general literature review of DO requirements for fish species in the Northern River basins (Barton and Taylor 1994). Most fish species in the Northern River basins spawn in spring. Their eggs incubate during spring or early summer and, thus, the early life stages experience little or no DO limitations. Acting on recommendations from the literature review report, the study funded two studies on the effects of lowered DO levels on developing eggs of fish species native to the Northern Rivers (Giles and Van der Zweep 1996; Giles et al. 1996). The species were selected on the basis of the literature review report (Barton and Taylor 1994) that compiled existing information on the DO requirements of fish species occurring within the NRBS area. This review concluded that while there was a considerable information on rainbow trout that could be applicable to salmonids in general, exceptions were bull trout, mountain whitefish and arctic grayling. Similarly, aside from adult fish and embryos of northern pike and walleye, there was a deficiency in our knowledge of the DO requirements of northern river fishes, particularly in relationship to the acute low oxygen tolerances of many species. Given that conditions of lowered DO occur during winter, fish species that spawn in fall or winter (namely mountain whitefish (Prosopium williamsoni), bull trout (Salvelinus confluentus) and burbot (Lota lota)) were selected for more detailed study. Table 5.1 shows the seasonal life stage characteristics of these three Northern River basins fish species.

5.2 LITERATURE REVIEW

In a study of the Wapiti-Smoky River, Swanson (1993) collected eggs from mountain whitefish with the aim of conducting laboratory experiments on the effects of hypoxia on embryo development. Insufficient eggs were collected, however, and the study was confined to histologic examination of the

Table 5.1 Seasonality of key life stages of several fish species found in the Northern River basins.

Northern River Basins Fish Species	**Spawning Season**	**Egg Incubation Season**	**Early Life Stages Season**
SeasonTrout Family - Salmonidae			
Mountain Whitefish *(Prosopium williamsoni)*	Sept. to Nov.	winter	spring and summer
Bull Trout *(Salvelinus confluentus)*	Sept. to Oct.	winter	spring and summer
Cod Family - Gadidae			
Burbot; or Maria, Ling, Loche *(Lota lota)*	Jan. to Mar.	winter	spring and summer

eggs. No conclusions were able to be drawn. Barton and Taylor (1994; in press) provided a comprehensive review of the DO requirements of fishes found in the Northern Rivers. They focused on environmental conditions in the Peace, Athabasca and Slave mainstems with particular reference to pulp mill effluent impacts and winter ice cover. Their report is subdivided into sections addressing: (1) anatomy and physiology of respiration in fish, (2) limnology of DO in northern rivers, (3) effects of adverse DO conditions on fish and invertebrates, (4) interactions of DO with pollutants and contaminants, (5) species and life requirements, and (6) information needs.

5.2.1 Summary of Key Findings From the Literature

The DO requirements of fish vary with season and life stage. Much research has been directed at determining the acute DO requirements of fish (i.e., the minimum DO concentration necessary to avoid short-term, potentially fatal hypoxia) with minimal research invested in the effects of chronic (i.e., the minimum DO concentration necessary for long-term growth and reproduction) and periodic diminishments of DO. Most of the current research has focuses on laboratory investigations at temperatures not typically experienced by northern fish species during winter under ice cover. More difficult to assess, and less well known for the species existing in the Northern Rivers, are the chronic effects and their implications for long-term growth and survival of Northern Rivers fish populations.

Barton and Taylor (in press) tentatively classified fish species living in the Northern Rivers in one of four groups. The groupings were based on very limited information for most of the northern fish species and based on the acute tolerances of adults. The DO requirements for embryos, fry and juveniles are usually greater than adults. Similarly, the DO requirements to sustain long-term health of a fish population are substantially higher than acute lethal limits and are also much more similar among species. The four level classification and groupings of northern river fishes are: (1) sensitive (acute limit >2 mg/L DO; includes all salmonids, longnose sucker and burbot); (2) intermediate (acute limit 1-2 mg/L DO; includes all cyprinids except fathead minnow, walleye, white sucker, brook stickleback and goldeye); (3) tolerant (acute limit <1 mg/L DO; includes fathead minnow, northern pike and yellow perch); and (4) unknown (insufficient information available; includes largescale sucker, ninespine stickleback, all sculpins, trout-perch).

Sufficient information is lacking for nearly all Northern Rivers fish species to establish chronic DO requirements necessary to ensure long-term maintenance of healthy fish communities. Earlier studies reviewed by Barton and Taylor (1994) recommended DO guidelines of 6 mg/L for salmonids and 5 mg/L for non-salmonids. Table 5.2 summarizes the recommended minimum DO concentrations to protect Northern River basins fishes during key life stages. Barton and Taylor (1994) could not make a firm recommendation of sentinel species for the northern rivers because even the most basic information on DO requirements is lacking for many species. They did, however, provide the tentative interim suggestion that mountain whitefish eggs and larvae, bull trout, burbot and longnose suckers be used as sentinel species to monitor DO conditions.

able 5.2 Minimum dissolved oxygen (DO) criteria for Northern River basins fish in various life stages. Note that early life stages include embryos (eggs) and larvae (Barton and Taylor, in press).

Life Stage	**Criteria Interval**	**Salmonids (except whitefishes)**	**Whitefishes**	**Non-salmonids**
		DO concentration (mg/L)		
Adult	7 day mean 7 day mean minimum	6.0 5.0	6.5 5.0	5.0 5.0
Fry	7 day mean 7 day mean minimum	6.5 5.5	6.5 5.5	6.0 5.0
Early Life (includes embryos [eggs] and larvae)	7 day mean 7 day mean minimum	9.5	6.5	6.0

5.3 OXYGEN STRESS EXPERIMENTS ON NATIVE FISH SPECIES

5.3.1 Bull Trout and Mountain Whitefish

A laboratory experiment was performed to determine the effects of varying degrees of hypoxia on egg incubation and early larval life stages of bull trout and mountain whitefish (Giles and Van der Zweep 1996). Bull trout eggs were obtained from a hatchery in British Columbia and mountain whitefish eggs were collected from the upper reaches of the Athabasca River in fall 1993. The eggs were incubated at DO concentrations of 3, 5, 7, 9 and 13.5 mg/L; all treatments were held at 2 C. Blood chemistry, gamete viability and embryo survival and development were measured. In the case of the 3oC treatment, water temperature was raised toward the end of the experiment to induce hatching. Alevins were also assessed for the influence of reduced DO on their critical thermal maxima.

DO concentrations as low as 3 mg/L at temperatures of 2-3oC had no significant effect on egg survival of either mountain whitefish or bull trout. However, mountain whitefish eggs incubated under these conditions took much longer to hatch than eggs incubated at higher DO levels. An inverse relationship between time to hatch and level of anoxia was observed. Bull trout eggs incubated at similarly low DO and temperature conditions exhibited a minimal time delay until hatching compared to mountain whitefish eggs, however emerged alevins were smaller (having consumed proportionately less of their yolk sac).

5.3.2 Burbot

A laboratory study on burbot was undertaken to evaluate the potential of winter water temperatures (3oC) and low oxygen levels (O2 = 6 mg/L; 45 % air saturation) to impair reproductive performance and induce stress in spawning burbot (Giles et al. 1996). The study assessed temporal changes in reproductive hormones; identified changes in blood electrolytes, haemoglobin, haematocrit and blood oxygen content in maturing adults; and evaluated the viability of gametes and fertilized eggs held under low (6 mg/L) and near ambient (13 mg/L) DO. Blood haematocrit and haemoglobin measurements were used to assess the carrying capacity of the gas transport system while blood electrolytes and glucose were used to monitor potential ionoregulatory disturbances and associated stress under hypoxic conditions. In addition to spawning activity, embryo survival and larval development, reproductive hormones, including adult steroid hormones (17B-estradiol, testosterone and 11-ketotestosterone) as well as attempts to determine gonadotropin II (GTH II) and vitellogenin, were used to assess reproductive ability.

Maturing burbot, captured at Elks Island on Lake Winnipeg, were held through the later stages of reproductive development in the laboratory at 3oC under conditions of either low DO (O2 = 6 mg/L) or near ambient DO (O2 = 13 mg/L). At approximately 5 week intervals throughout gonadal development, blood samples were removed from maturing adult fish. Eggs were collected from the holding tanks, after being spawned by the adults, on several occasions from late January to early March 1995. Eggs were incubated under the same low and ambient DO conditions as the adults.

Adult burbot exposed to low and ambient DO conditions showed few consistent differences in blood haematocrit and haemoglobin or plasma electrolyte balance and glucose. This suggests that a DO concentration of 6 mg/L lies within the compensatory scope of homeostatic processes in burbot. However, the long-term costs of this compensation on metabolism remain to be established. Low DO conditions (6 mg/L) appeared to extend spawning as much as 5 weeks in some burbot. While maintenance of maturing burbot under hypoxic conditions produced only minor changes in the reproductive steroids, the differences were consistent with the extended spawning. Indices of embryological development were unaffected by incubation conditions. Because it proved impossible to manually strip eggs from female burbot, it was not possible to follow individual spawners and their gametes. Thus, observations about the effects of low DO on spawning activity, embryo survival, development and hatch are regarded as preliminary. However, the observation that low DO conditions (6 mg/L) extended the time required to hatch is consistent with findings from the Northern River Basins study of mountain whitefish by Giles and Van der Zweep (1996).

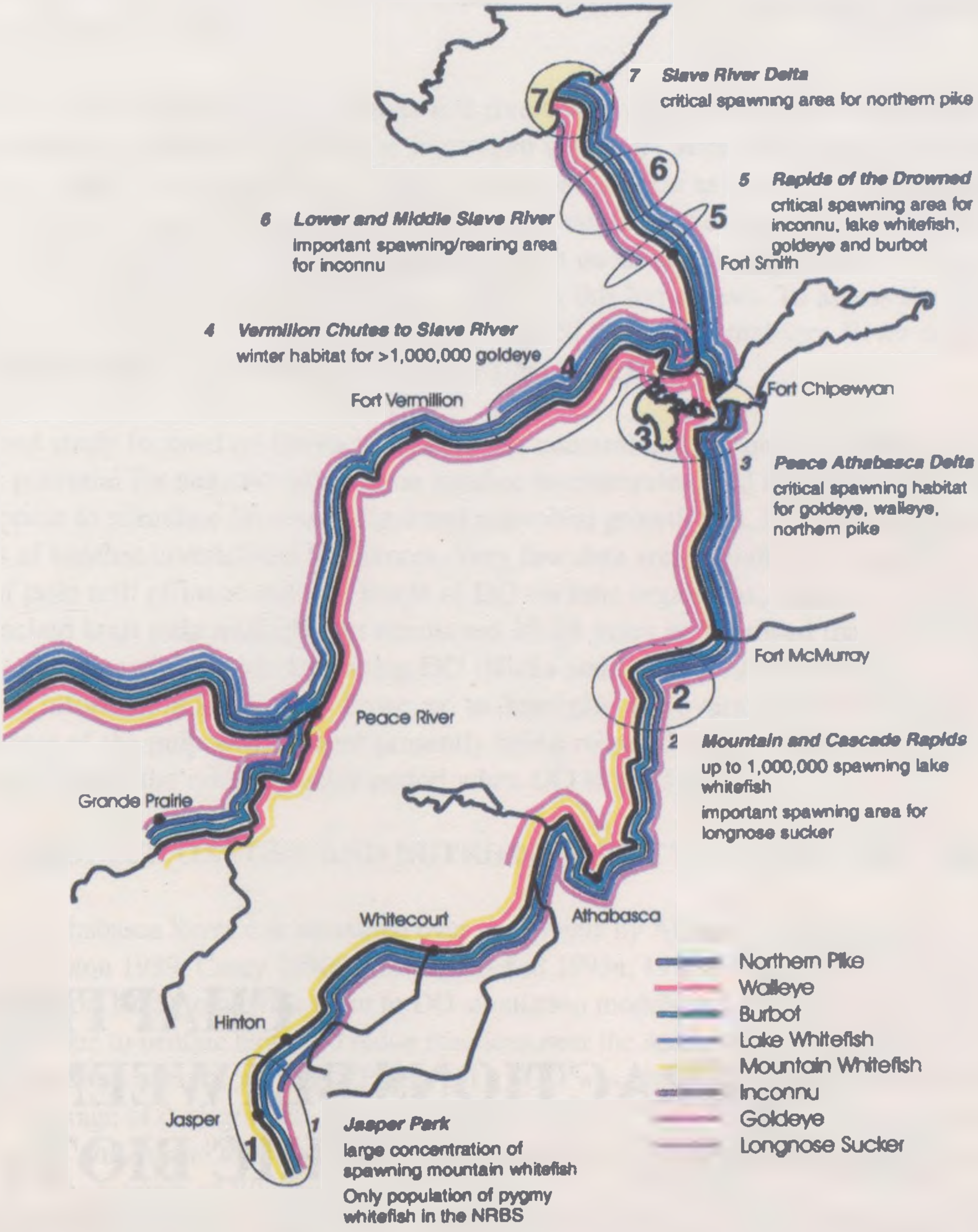
The Northern River Basins study by Giles and Van der Zweep (1996) represents the first attempt to perform a detailed investigation of burbot reproduction. Due to a variety of difficulties encountered with the spawning, incubation and hatching of burbot, the findings must be considered very preliminary. Future investigations need to consider that it is extremely difficult to spawn burbot manually and that they spawn at night. Nevertheless, the physiological and reproductive parameters found in the laboratory-held burbot in this study were similar to those observed in burbot collected from the reference areas in the Peace, Athabasca and Slave rivers (Brown *et al.* 1996). Thus, the results reported here provide important comparative information for the coincident field collection programs. There is need for more work with this species and because of its wide distribution within the Northern Rivers, it may be a useful sentinel species for monitoring low DO conditions.

5.4 ASSESSMENT

The effects of low DO (3 mg/L) on embryonic development in mountain whitefish and bull trout eggs occurred at later stages of incubation. These stages are found in the rivers during late winter when heavy ice cover has developed and the largest DO sags occur. Preliminary results from experiments with burbot also suggest that lowered DO concentrations (6 mg/L) extended spawning. DO concentrations of less than 5 mg/L or even less than 6.5 mg/L are generally not observed in the mainstem of the Athabasca River (see Section 3.3). However, many tributaries of the Athabasca River (notably the Pembina, Lac LaBiche, Muskeg and Firebag rivers) have winter DO concentrations that are frequently less than 5 mg/L. Given the fact that eggs and early life stages live at or in the surface layers of the riverbed and that DO concentrations can differ by 3 mg/L DO between the water column and the sediment-water interface (Chapman 1986), DO concentrations in the Athabasca River could already be at levels that induce developmental delays in incubating eggs of these fish species at localized sites. Detailed investigations of egg incubation and early rearing habitat for fish in the Northern River basins were not undertaken.

However, based upon best knowledge of fish habitat, it is likely that the sites of egg spawning and incubation which experience lowered DO are not extensive and represent negligible quantities of the known and suspected incubation and early rearing habitat for bull trout, mountain whitefish and burbot in the Athabasca River and its tributaries (Figure 5.1). Consequently, it is unlikely that low DO concentrations are having measurable effects on populations of these species at present.

Figure 5.1 Distribution and critical sites for spawning or overwintering of Northern Pike, Walleye, Burbot, Lake Whitefish, Mountain Whitefish, Inconnu and Goldeye in the Athabasca, Wapiti, Smoky, Peace and Slave rivers (Wrona et al. 1996)



7 ***Slave River Delta***
critical spawning area for northern pike

5 ***Rapids of the Drowned***
critical spawning area for inconnu, lake whitefish, goldeye and burbot

6 ***Lower and Middle Slave River***
important spawning/rearing area for inconnu

4 ***Vermilion Chutes to Slave River***
winter habitat for >1,000,000 goldeye

3 ***Peace Athabasca Delta***
critical spawning habitat for goldeye, walleye, northern pike

2 ***Mountain and Cascade Rapids***
up to 1,000,000 spawning lake whitefish
important spawning area for longnose sucker

1 ***Jasper Park***
large concentration of spawning mountain whitefish
Only population of pygmy whitefish in the NRBS

CHAPTER 6.0

INTERACTIONS BETWEEN THE RESPONSE OF BENTHIC BIOTA TO DISSOLVED OXYGEN AND NUTRIENTS OR CONTAMINANTS

6.0 INTERACTIONS BETWEEN THE RESPONSE OF BENTHIC BIOTA TO DISSOLVED OXYGEN AND NUTRIENTS OR CONTAMINANTS

The aim of this chapter is to review studies undertaken by the NRBS to assess: (1) the effects of enhanced periphyton growth due to nutrient loading from pulp mills discharges on consumption of oxygen near the streambed (Section 6.1), and (2) the combined impacts of low winter DO concentrations and pulp mill effluent on a common northern river invertebrate, the mayfly Baetis tricaudatus (Section 6.2).

In the case of the first study, observations that rivers with elevated nutrient concentrations have DO concentrations below saturation due to oxygen uptake by abundant growths of aquatic plants (e.g., MacCrimmon and Kelso 1970) raised the question as to whether the abundant periphyton growth found below pulp mill discharges could be the major source of SOD. The fact that lakes with high nutrient concentrations often go anoxic during winter due to bacterial demands for oxygen (Wetzel 1983) is consistent with this hypothesis. To assess the role of periphyton production in SOD, temporal changes in SOD in the Athabasca River during winter were examined and correlated with periphyton algal biomass.

The second study focused on interactions between contaminants in pulp mill effluents, which have the potential for negative impacts on benthic invertebrates, and nutrients in the effluents, which appear to stimulate increased algal and microbial growth and, in turn, increase the densities of benthic invertebrate herbivores. Very few data are available to assess the combined effects of pulp mill effluent and low levels of DO on lotic organisms; however, previous work with bleached kraft pulp mill effluent conducted 15-25 years ago showed that contaminant toxicity to fish increased with decreasing DO (Hicks and DeWitt 1971; Graves et al. 1981). Additional information is required, however, to determine the overall effect on benthic invertebrates of the pulp mill effluent presently being released in the Northern Rivers, particularly during the critical winter period when DO is at its lowest.

6.1 DISSOLVED OXYGEN AND NUTRIENT IMPACTS ON BENTHIC BIOTA

SOD in the Athabasca River was measured over six winters by Alberta Environmental Protection (Casey and Noton 1989; Casey 1990; HBT AGRA Ltd 1993a, 1993b, 1994) and NRBS (Monenco Inc. 1992; Noton 1995) to provide input to DO simulation models and assess changes in DO consumption due to benthic biota and redox reactions near the sediment:water interface. SOD showed a consistent pattern over the six years (Figure 6.1): SOD was high below Weldwood of Canada Ltd. at Hinton (average of 0.31 g/m2/d), dropped quickly within approximately 50 km downstream of Hinton to 0.12 g/m2/d and then decreased further over the next approximately 150 km to an average of 0.02 g/m2/d upstream of Whitecourt. Below Whitecourt, levels again rose to an average of 0.38 g/m2/d, decreased quickly over the next 40-50 km to 0.14 g/m2/d after which SOD remained relatively stable at this rate. This increase in SOD below the Hinton and Whitecourt effluent outfalls may be due to decomposition of: (1) nutrient-enhanced periphyton or carbon-enhanced bacterial communities below the outfalls, and/or (2) particulate carbon released by the mills.

The higher SOD rates downstream of mill outfalls corresponds to zones of nutrient enrichment characterized by high periphyton biomass, elevated benthic invertebrate densities and, in the case of the Hinton outfall, longer heavier specimens of a small fish species (see review in Chambers 1996). The co-occurrence of high SOD and high biotic productivity raises the question of whether decomposition of the enhanced periphyton growth (caused by nutrient loading from the pulp mills) is responsible for the increased SOD downstream of pulpmill outfalls. If the periphyton is the main factor determining SOD rates, then decomposition over winter (due to the effects of reduced light and temperature) could result in increasing SOD. While SOD rates were found to increase over the winter in open-water areas (Casey 1990), studies over the 1993-1994 (HBT AGRA Ltd. 1994) and 1994-1995 (Noton 1995) winters showed no increase in SOD in ice-covered areas. As well, benthic chlorophyll a concentrations from within SOD chambers showed no relationship to SOD rates at ice-covered sites for January-March 1994 ($r2=0.007$, $P>0.05$) and a weak but significant relationship ($r2=0.29$, $P=0.002$, Noton 1995) for October 1994 to March 1995 (Figure 6.2). One explanation for these findings may be that the high SOD below pulp mill outfalls is not caused by decomposition of nutrient-enhanced periphyton production.

As a first test of the hypothesis that SOD below mill outfalls was related to deposition and subsequent decomposition of particulate carbon released in the effluent, sedimentation rates (km-1) downstream of Hinton were calculated from suspended sediment transport data of Krishnappan et al. (1995) for under-ice conditions in 1993 and compared with SOD rates for the same period (HBT AGRA Ltd. 1993b). While data are limited, the longitudinal pattern in sedimentation was similar to that of SOD (Figure 6.3a). Regression analysis also showed a significant relationship between ln-transformed SOD and sedimentation ($r2=0.96$; $P<0.05$). Sediment organic content collected along the Athabasca River in spring 1993 as part of the NRBS was also significantly correlated with SOD (ln of SOD versus sediment organic content; $r2=0.74$, $P>0.1$; Figure 6.3b). These findings, as well as similarities in the longitudinal distribution of SOD and water-column particulate and dissolved carbon and turbidity downstream of Hinton (Figures 6.3c, d), suggest that SOD is related to the mill effluent. However, the high sediment organic content, water-column particulate carbon concentration and turbidity upstream of Hinton suggest that some of the organic carbon in the sediments downstream of Hinton is also from natural sources. If mill effluent is an important factor driving SOD and considering that there is no evidence of increasing SOD over the winter (HBT AGRA Ltd. 1994; Noton 1995), then the microbial processes responsible for organic matter breakdown and oxygen consumption must be in balance with the rate of sedimentation of organic material. While these data sets are small and limited to one year and cannot be used to infer cause and effect, they do suggest that SOD downstream of Hinton is related in part to the Weldwood of Canada Ltd. mill effluent, possibly to particulate and/or dissolved organic carbon loading. Further studies are needed to clearly quantify the link, if any, between SOD and decomposition of particulate carbon derived from pulp mill effluents.

If SOD is related to organic carbon and/or nutrient loading from pulpmill effluent, then the question arises as to why the longitudinal pattern of SOD differs below Hinton and Whitecourt (Figure 6.1). The difference in SOD patterns below mill outfalls may be due to many factors including differences in the quality of the mill effluents (Weldwood of Canada Ltd. is a kraft pulp mill; Alberta Newsprint Co. and

Figure 6.1 Sediment oxygen demand (SOD, mean ± S.E.) in the Athabasca River for the 1989, 1990, 1992, 1993, 1994 and 1995 winters (Casey and Noton 1989; Casey 1990; Monenco Inc. 1992; HBT AGRA Ltd. 1993b; HBT AGRA Ltd. 1994; Noton 1995).

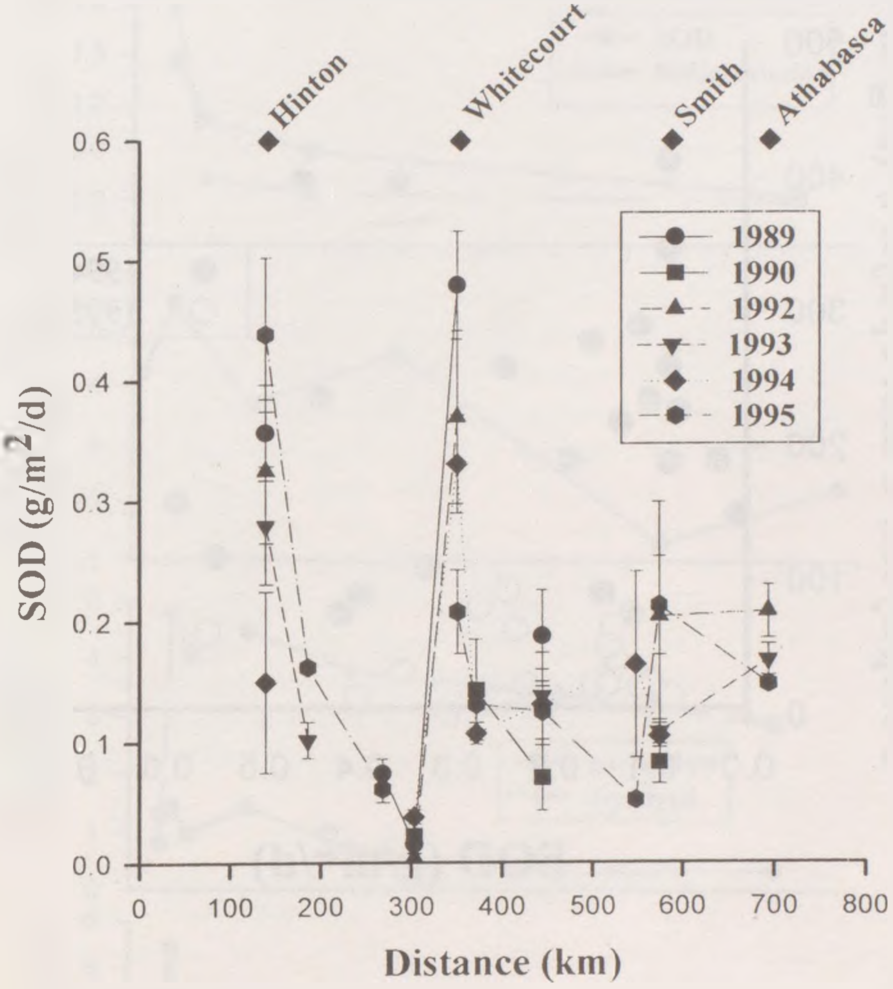


Figure 6.2 Sediment oxygen demand (SOD) versus periphyton chlorophyll a concentrations for the Athabasca River during winter (January-March 1994; HBT AGRA Ltd. 1994; January-March 1995; Noton 1995).

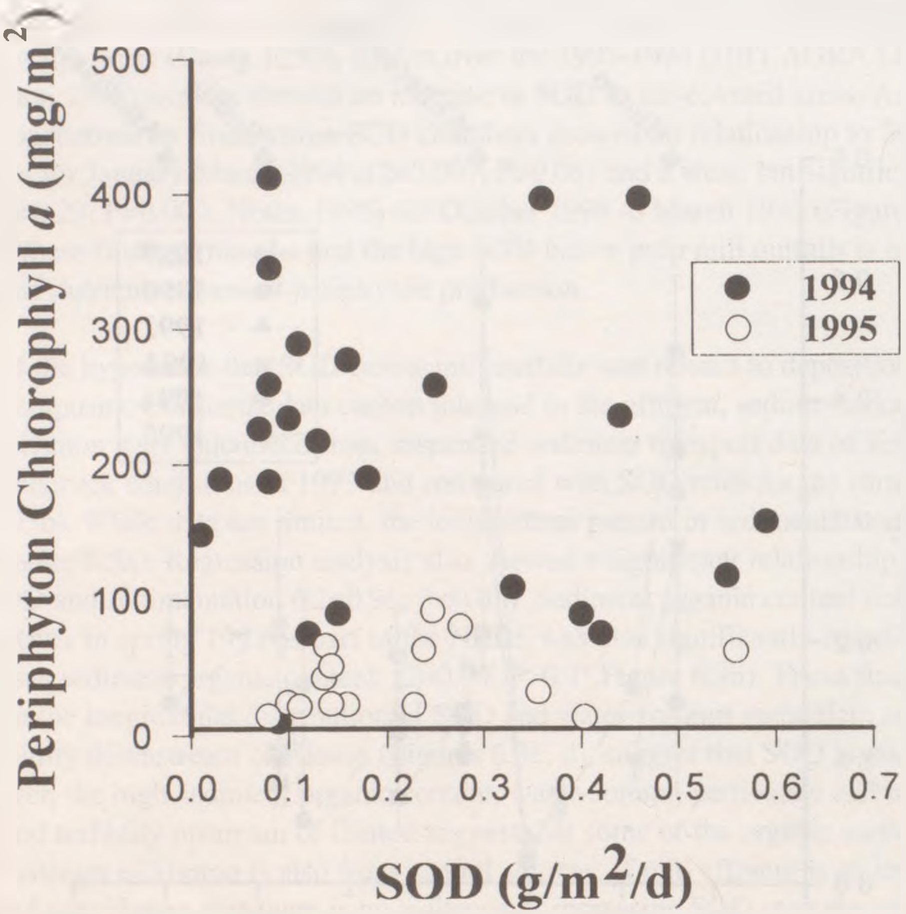
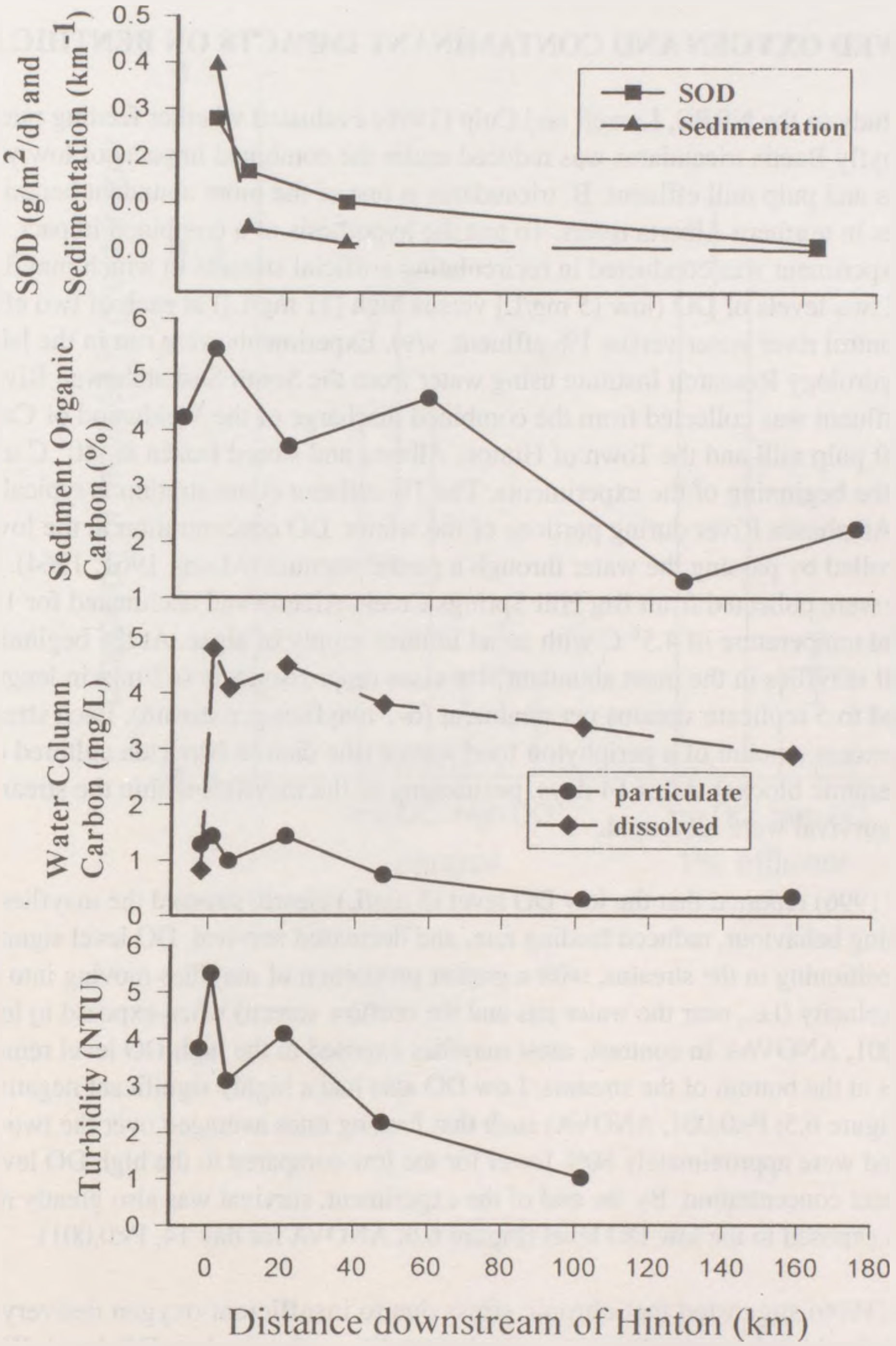


Figure 6.3 Sediment oxygen demand (SOD), sedimentation, sediment organic carbon, water-column particulate carbon and turbidity for the Athabasca River. SOD data from HBT AGRA Ltd. (1993b), sedimentation data from Krishnappan et al. (1995), sediment organic carbon data from NRBS Reach Specific Survey and water-column particulate carbon and turbidity data from Alberta Environment winter water quality surveys.



Millar Western Pulp Ltd. are chemi-thermomechanical pulp mills), changes in the physical attributes of the river (e.g., the river at Hinton has a narrower cobble bed and widens to a mud/silt bed downstream), and changes in nutrient availability for the benthic microbial community. These initial findings on the source of the elevated SOD below mill outfalls indicate that assessment and simulation modelling of future loading scenarios to the river should consider the effect of both the BOD load and the quality of the effluent on SOD.

6.2 DISSOLVED OXYGEN AND CONTAMINANT IMPACTS ON BENTHIC BIOTA

In a companion study to the NRBS, Lowell and Culp (1996) evaluated whether feeding rate and survival of the mayfly Baetis tricaudatus was reduced under the combined impacts of low winter DO concentrations and pulp mill effluent. B. tricaudatus is one of the more abundant benthic macroinvertebrates in northern Alberta rivers. To test the hypothesis of a combined impact, a 2x2 factorial design experiment was conducted in recirculating artificial streams in which mayflies were exposed to one of two levels of DO (low [5 mg/L] versus high [11 mg/L]) at each of two effluent concentrations (control river water versus 1% effluent, v/v). Experiments were run in the laboratory at the National Hydrology Research Institute using water from the South Saskatchewan River. Full strength treated effluent was collected from the combined discharge of the Weldwood of Canada Ltd. bleached kraft pulp mill and the Town of Hinton, Alberta and stored frozen at -40° C until dilution to 1% at the beginning of the experiments. The 1% effluent concentration is typical of full-mix levels in the Athabasca River during portions of the winter. DO concentration in the low DO streams was controlled by passing the water through a partial vacuum (Mount 1961, 1964). B. tricaudatus larvae were collected from Big Hill Springs Creek, Alberta and acclimated for 10 days at the experimental temperature of 4.5° C with an ad libitum supply of algae. At the beginning of the experiment, all mayflies in the most abundant size class (approximately 6-7 mm in length) were randomly allocated to 5 replicate streams per treatment (6-7 mayflies per stream). Each stream was supplied with an excess amount of a periphyton food source (the diatom Navicula cultured on 2.4x2.4x0.5 cm ceramic blocks). After 14 days, positioning of the mayflies within the streams, feeding rate, and survival were measured.

Lowell and Culp (1996) reported that the low DO level (5 mg/L) clearly stressed the mayflies leading to altered positioning behaviour, reduced feeding rate, and decreased survival. DO level significantly affected mayfly positioning in the streams, with a greater proportion of mayflies moving into regions of higher current velocity (i.e., near the water jets and the outflow screen) when exposed to low DO (Figure 6.4; $P<0.001$, ANOVA). In contrast, most mayflies exposed to the high DO level remained on the ceramic blocks at the bottom of the streams. Low DO also had a highly significant negative effect on feeding rate (Figure 6.5; $P<0.001$, ANOVA) such that feeding rates averaged over the two-week experimental period were approximately 80% lower for the low compared to the high DO level, regardless of effluent concentration. By the end of the experiment, survival was also greatly reduced for those mayflies exposed to the low DO level (Figure 6.6; ANOVA for day 14, $P<0.001$).

Lowell and Culp (1996) suggested that chronic stress due to insufficient oxygen delivery to the gills and reduced food intake caused the increased mortality under the low DO level. While the low DO level

Figure 6.4 Proportion of mayflies positioned in regions of greater flow within the artificial streams (daily mean averaged over 2 weeks, ±1 SE) at two concentrations (control, 1% effluent) and two DO levels.

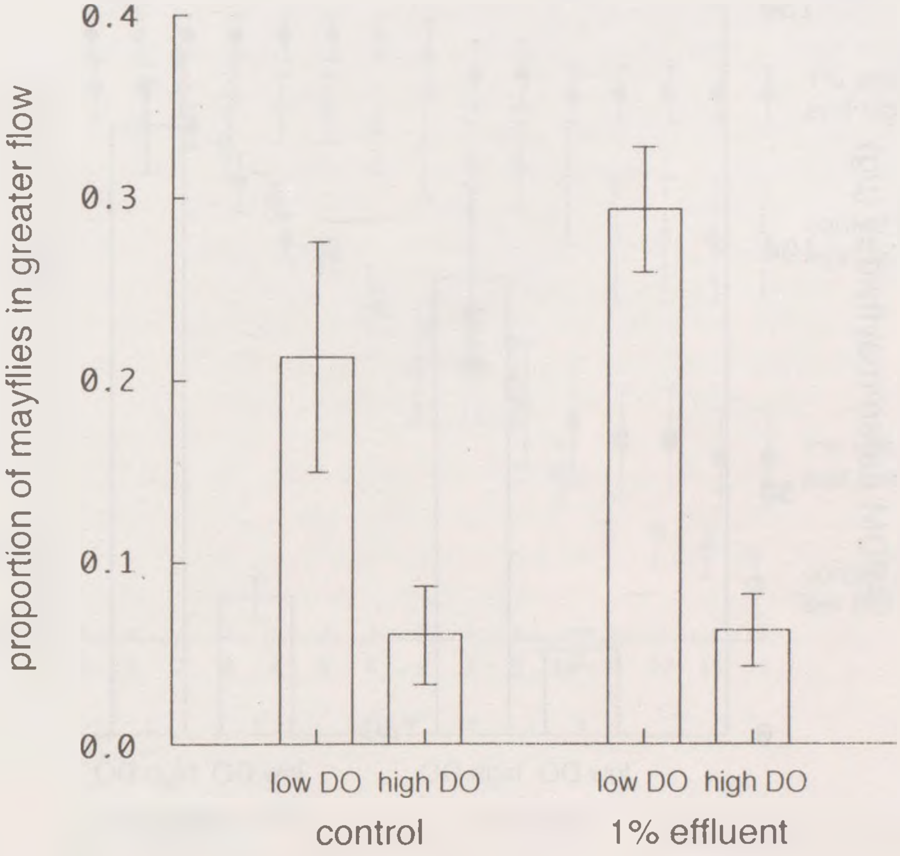


Figure 6.5 Feeding rate of mayflies (daily mean averaged over 2 weeks, ±1 SE) at two concentrations (control, 1% effluent) and two DO levels. AFDM - ash-free dry mass.

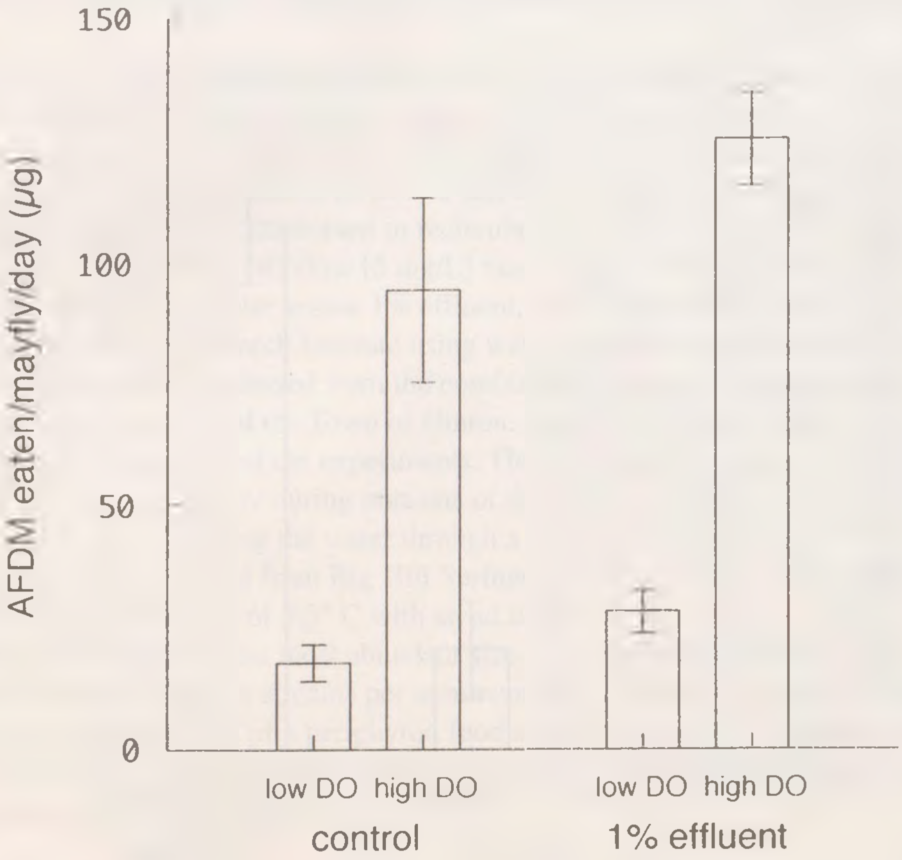
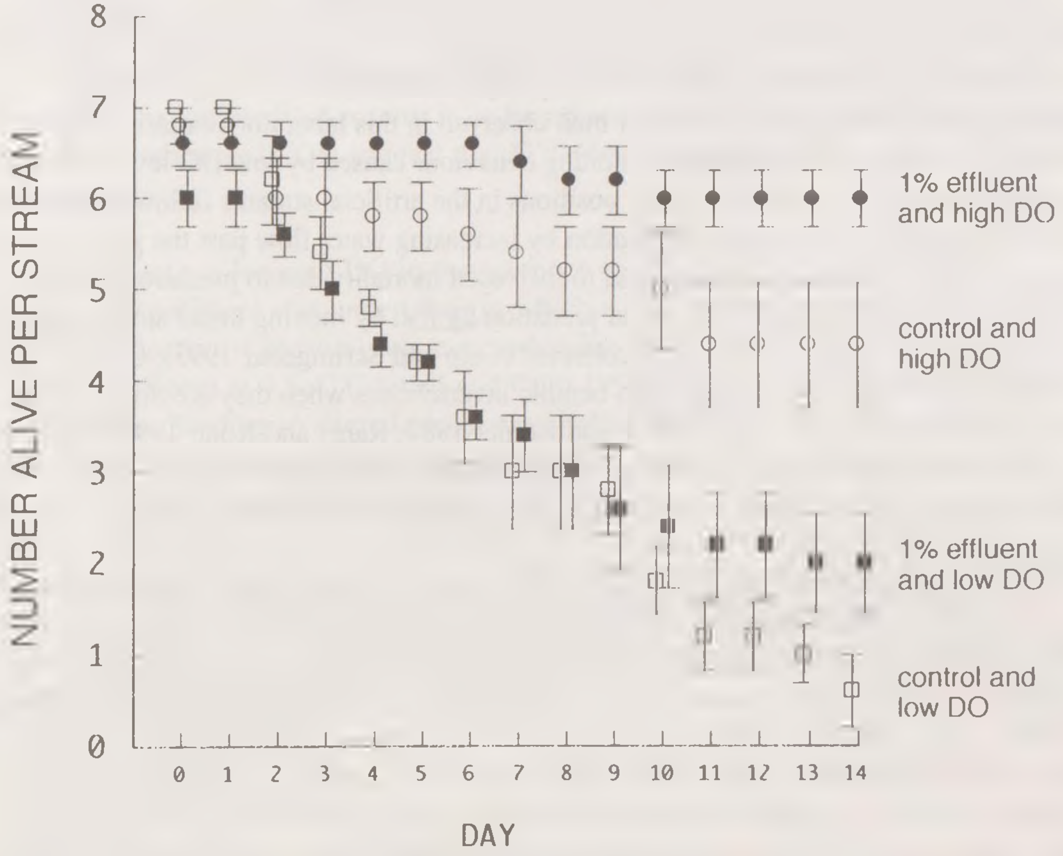


Figure 6.6 Survival of mayflies over 14 day experimental period (±1 SE) at two concentrations (control, 1% effluent) and two DO levels.



(5 mg/L) was less than is typically observed in the water column of the Athabasca River during winter, water-column DO concentrations as low as 2.8 mg/L have been reported in regions of groundwater or tributary inflow (Section 3.3). Moreover, studies on trout-spawning substrata in other rivers have shown that DO levels in the substratum may be 3 mg/L lower than that in the overlying water (Chapman 1986). Since mayflies and other benthic invertebrates typically range into the substratum, they may experience DO levels considerably lower than water-column values. Thus, some individuals in the Athabasca River are likely exposed to DO levels 5 mg/L. Indeed, survivorship in the field may be even lower than observed in this laboratory experiment due to the indirect negative effects of the altered positioning behaviour caused by low DO levels. The mayflies in this experiment moved to more elevated positions in the artificial streams following exposure to low DO levels, probably to facilitate respiration by increasing water flow past the gills. Previous studies suggest that this response would lead to increased mortality due to predation since B. tricaudatus typically seek refuge from visual predation by fish by moving under stones, particularly during daylight hours when our data were collected (Culp and Scrimgeour 1993). Other studies have also demonstrated increased predation upon benthic invertebrates when they are driven into more exposed locations by low DO levels (Wiley and Kohler 1980; Rahel and Kolar 1990; Pihl et al. 1992). On the other hand, Lowell and Culp (1996) point out that in the river, mortality of mayflies due to low DO may be lessened at lower temperatures or greater acclimation periods.

In contrast to the negative effects of low DO, the 1% effluent treatment increased survival at least over the two week course of the experiment (Figure 6.6; ANOVA for day 14, P=0.002). Effluent concentration did not significantly affect mayfly positioning (P>0.34; ANOVA) although the 1% effluent may have stimulated (P=0.080; ANOVA) an increase in feeding rate (Figure 6.5). Neither survival, feeding rate nor positioning was affected by concentration-DO interaction effects (P=0.868, 0.357 and 0.473, respectively; ANOVA). Lowell and Culp (1996) noted that the effluent-associated increase in survival at the high DO level was due in part to unusually low survival (33%) in one replicate stream in the control concentration-high DO treatment. But the effluent-enhanced increase in survival at the low DO level may have also been due to the possible stimulation of an increase in feeding rate by the effluent; this may have partly offset the even greater reduction in feeding rate caused by the low DO level. In an earlier study, Lowell et al. (1995) observed that pulp mill effluent can stimulate increased short-term growth and development of B. tricaudatus and proposed that this growth stimulation may have been caused by an effluent-induced increase in feeding rate. They also suggested other possible mechanisms for this effect, including: (a) increased nutritive value of the periphyton, and (b) hormonal or other growth-stimulating effects of the compounds in pulp mill effluent. Further work is required, however, to determine whether these positive short-term effects of pulp mill effluent involve trade-offs against other longer-term fitness measures, such as fecundity.

6.3 ASSESSMENT

Elevated SOD rates are observed during winter below the Hinton and Whitecourt discharges and have been speculated to be caused by decomposition of the nutrient-enhanced periphyton growth found below the outfalls. Analysis of SOD rates measured at ice covered sites over the

1993-1994 (HBT AGRA Ltd. 1994) and 1994-1995 (Noton 1995) winters showed no increase in SOD and either no correlation (January to March 1994) or only a weak correlation (October 1994 to March 1995) with benthic chlorophyll a concentrations sampled from within the SOD chambers. These findings suggest that the high SOD below pulp mill outfalls may not be caused by decomposition of nutrient-enhanced periphyton production. The elevated SOD observed below mill outfalls may be due in part to deposition and subsequent decomposition of particulate carbon released in the effluent. While data were limited to test this hypothesis, similarities in the the longitudinal pattern in sedimentation, water-column particulate carbon, sediment organic carbon and SOD suggest that SOD downstream of mill outfalls is related to organic carbon loading.

To evaluate the effects of lowered DO in the presence of pulp mill effluent on benthic invertebrates, an experiment was undertaken in which a commonly-occuring mayfly in the Northern Rivers (Baetis tricaudatus) was exposed to low DO concentrations (5 mg/L) and 1% treated pulp mill effluent at 4.5oC (Lowell and Culp 1996). The low DO level (5 mg/L) clearly stressed the mayflies leading to altered positioning behaviour, reduced feeding rate, and decreased survival. The presence of the effluent had either no or a positive (i.e., increased feeding rate) effect. DO concentrations of less than 5 mg/L are generally not observed in the mainstem of the Athabasca River (see Section 3.3). However, given the fact that mayflies live at or in the surface layers of the riverbed and that DO concentrations can differ by 3 mg/L DO between the water column and the sediment-water interface (Chapman 1986), DO concentrations in the Athabasca River could already be at levels that could have chronic effects on these animals at localized sites.

CHAPTER 7.0
OVERALL ASSESSMENT

7.0 OVERALL ASSESSMENT

This report addresses the Northern River Basins Study (NRBS) question: "What concentrations of dissolved oxygen are required seasonally to protect the various life stages of fish, and what factors control dissolved oxygen (DO) in the rivers?" The purpose of this report was to assess the loading of oxygen-consuming waste from pulp mills, municipalities and other industrial sources on the Athabasca, Wapiti, Smoky, Peace and Slave rivers and evaluate the impacts of these loads on the biota of these rivers. During the past four years, studies have been undertaken as part of the NRBS to characterize loading from all point sources in the Northern River basins, evaluate the impacts of oxygen-consuming waste on river chemistry, develop models for predicting DO concentrations in the Athabasca River, assess the response of riverine biota to low DO levels, and investigate interactions between low DO levels and nutrients and contaminants in pulp mill effluent on benthic organisms. This report synthesizes results from monitoring, research and simulation modelling studies on the impacts of oxygen-consuming waste on water quality, with the aim of providing an assessment of the state of aquatic ecosystem health and management recommendations for the Northern River basins.

7.1 DO CONDITIONS IN THE NORTHERN RIVERS

The Athabasca River receives effluent from 15 continuous-discharge point sources (five pulp mills, one oil sands project and nine municipalities with one mill and one municipality having a combined discharge). The Wapiti River receives effluent from two continuous-discharge point sources (a pulp mill and a municipality) while the Smoky River receives continuous-discharge effluent from the Wapiti River sources as well as from one additional municipality. The Peace River receives effluent from five pulp mills (two in the NRBS area) and four sources of continuous-discharge sewage, in addition to the sources on the Wapiti-Smoky rivers. The Slave River receives effluent from all the Peace and Athabasca sources as well as from one continuously-discharging STP (Fort Smith). Concern about DO conditions in the Northern Rivers focuses on the ice-covered period when only limited reaeration occurs to replenish any oxygen consumed by oxygen-consuming effluent, river biota and naturally-occurring chemical processes. In the Athabasca, Wapiti and Smoky rivers, DO concentrations decrease along the length of the rivers with sags in DO occurring below some pulp mill discharges in certain winters. In the case of the Athabasca River, DO concentrations remain relatively constant and approach saturation from the headwaters to upstream of Hinton. Thereafter, concentrations decrease to Grand Rapids where a 10 m cascade keeps the water open year-round and reaerates DO levels back to saturation. After Grand Rapids, DO concentrations once again begin to decline. Sags in DO were observed below Weldwood of Canada Ltd. in most winters and below Millar Western Pulp Ltd. during the 1989 start-up winter. In the Wapiti-Smoky rivers, DO concentrations decrease by 2-4 mg/L from upstream of Grande Prairie to the mouth of the Wapiti River and, in the Smoky River, continue to decline by 2-3 mg/L to Watino. Oxygen depletion is minimal in the mainstem of the Peace River during the winter due to low BOD5 concentrations, reaeration at Vermillion Chutes and perhaps Boyer Rapids, and the fact that the water column is saturated with oxygen as it enters Alberta and the reach from the British Columbia border to Peace River remains ice-free for much of the winter

(Shaw et al. 1990). While longitudinal data on DO concentrations in the Slave River are not available, it is unlikely that there is any appreciable decline in DO concentrations with distance.

Historical data from 1958-1995 for the Athabasca River indicate that late winter DO concentrations downstream of Hinton were lowest during the 20-years following the 1957 start-up of the Hinton mill and have since increased significantly ($P< 0.05$) at both Whitecourt and Athabasca. Historical data from 1966-1992 for the Wapiti-Smoky rivers indicate that winter DO concentrations have remained constant upstream of Grande Prairie before and after the 1973 start-up of the Weyerhaeuser Canada Ltd. mill but have decreased significantly in the Smoky River since 1973. DO concentrations in the Athabasca River since 1955 have rarely fallen below the Alberta Surface Water Quality Objective (Alberta Environment 1977) of 5 mg/L DO (Noton and Shaw 1989; Noton and Allan 1994; NRBS historical DO database). There have, however, been occasional observations of low DO (< 5 mg/L) on the mainstem during pulp mill monitoring studies (Beak Consulting Ltd. 1990; HBT AGRA 1994; Shelast and Brayford 1995) and these have been attributed to the samples being influenced by near-shore conditions or taken in zones where mixing was incomplete. A few tributaries to the Athabasca have winter DO concentrations less than the 5.0 mg/L objective on a fairly consistent basis: the Pembina, Lac La Biche, Muskeg and Firebag rivers. DO concentrations in the Wapiti-Smoky rivers (Noton 1992) or the Peace River (Shaw et al. 1990) have never been less than the 5 mg/L objective.

7.2 MODELLING OF DO CONDITIONS IN THE NORTHERN RIVERS

In addition to water quality monitoring, more recent studies of DO in the Athabasca River have expanded to include simulation modelling of DO dynamics. Water quality models are important tools for estimating the impact of nutrient, contaminant and biochemical oxygen demand (BOD) loadings on water and sediment chemistry, and biota in rivers. Often these models represent the best information available to decision makers in assessing the effects of existing and future loading scenarios. As part of the NRBS, the water quality simulation model DOSTOC was tested for use on the Athabasca River (Macdonald and Radermacher 1993). Input parameters for DOSTOC were also tested and validated for their applicability to the Athabasca River (Chambers et al. 1996). When DOSTOC was implemented using only in situ or laboratory measurements for all input parameters (with the exception of temperature correction coefficients), the simulations gave a reasonable fit to the observed data (i.e., r2 0.74) for January 1989 and the 1990-1993 winters with 74% of the observed DO values falling inside the 90% confidence limits (Chambers et al. 1996). Discrepancies between predicted and observed DO concentrations usually occurred in sag zones immediately below pulp mill discharges which may be related to the lack of the information on nitrogenous oxygen demand. Simulations for the 1994 winter were undertaken as part of this report and also showed a good fit (r2=0.79) to the observed data. These modelling results indicate that reasonable simulation could be expected for the Athabasca River between Hinton and Grand Rapids for more recent years (1990 - 1994). The modelling results were surprisingly good since no calibration was performed: all input measurements and rates were laboratory or in situ measurements for the Athabasca River and its tributaries, industries and STP's with the exception of temperature correction factors. Poorer predictions in early years (1988 and March 1989) may have related to the limited data on tributary and sewage inputs and mainstem DO concentrations for 1988 and, in March 1989, to the large and erratic BOD loadings from Millar Western Pulp Ltd. which had likely not equilibrated with instream processes. The fact that the model successfully predicted DO concentrations for the 1990 to 1993 winters was encouraging given that discharge of the Athabasca River at Athabasca varied from 62 m3/s in 1993 to 117 m3/s in 1990. To test the impact of mill effluent on DO concentrations in the Athabasca River, mill BOD loads were removed from the simulations with the result that DO concentrations at Grand Rapids increased by 0.2 to 0.4 mg/L (1990-1994).

In addition to DO simulation modelling undertaken by NRBS, Golder Associates Ltd. (1995) recently implemented WASP on behalf of Alberta Forestry Products Association and Alberta Environmental Protection to address temporal variations in DO. They found that while longitudinal changes in river-water DO concentrations were reasonably well predicted, temporal changes in river-water DO could not be modelled without adjusting open-water reaeration rates each year to match the predicted and the observed DO concentrations. This approach of adjusting the reaeration rate based upon measured DO values does not allow predictions of future scenarios; however, they noted that reaeration rates and air temperature may be correlated and suggested that this relationship could be further explored for future use in predicting DO. Discrepancies were also observed between BOD settling, water-column BOD decay, sediment BOD decay and reaeration rates that were calibrated in the WASP modelling (Golder Associates Ltd. 1995) compared to the measured values used in the DOSTOC modelling (Chambers et al. 1996).

7.3 DO DEMANDS BY BIOTA IN THE NORTHERN RIVERS

In the Northern Rivers, most fish species spawn in spring. Their eggs incubate during spring or early summer and, thus, the early life stages for larval fish and fry experience little or no DO limitations. However, several fish species, including mountain whitefish (Prosopium williamsoni), bull trout (Salvelinus confluentus) and burbot (Lota lota) spawn in fall or winter and their eggs incubate during winter with the early life stages occurring in spring and summer. A survey of information on the effects of low DO concentrations on fall or winter spawning fish species in ice-covered rivers revealed that while acute DO levels (i.e., the minimum DO concentration necessary to avoid short-term, potentially fatal hypoxia) have been studied for many fish species (although rarely at winter temperatures), very little is known about chronic DO requirements (i.e., the minimum DO concentration necessary for long-term growth and reproduction), especially for Northern Rivers' fish populations (Barton and Taylor 1994). In addition, little is known about the effects of lowered DO on benthic invertebrates and the indirect effects of reduced food supply (caused by DO stress on benthic invertebrates) on fish experiencing DO stress. Moreover, the addition of contaminants to the environment of fishes may exacerbate the effects of lowered DO concentrations by increasing metabolic rates or interfering directly with oxygen uptake across the gills.

To address the lack of information on chronic DO requirements by fish, laboratory experiments were performed to determine the effects of varying degrees of hypoxia on egg incubation and early larval life stages of bull trout, mountain whitefish and burbot (Giles and Van der Zweep

1996; Giles et al. 1996). DO concentrations as low as 3 mg/L at temperatures of 2-3oC were found to have no effect on egg survival of either mountain whitefish or bull trout. However, mountain whitefish eggs took much longer to hatch than eggs incubated at higher DO levels while bull trout alevins were less well developed (having consumed proportionately less of their yolk sac) when hatched from eggs held at 3 mg/L DO and 2-3 oC than when incubated at higher DO concentrations. DO concentrations of 6 mg/L may also extend the time required to hatch by some burbot. Given that the larval stages of these fish are found in the rivers during late winter and that DO concentrations within spawning beds (i.e., in the riverbed) are generally 3 mg/L less than in the water column, DO and temperature regimes in the rivers during these time periods could already be at levels that induce developmental delays in incubating eggs of these fish species at localized sites. While detailed investigations of egg incubation and early rearing habitat for fish in the Northern River basins were not undertaken, it is likely that the sites of egg incubation which experience lowered DO are not extensive and represent negligible quantities of the known and suspected incubation and early rearing habitat for bull trout, mountain whitefish and burbot in the Northern River basins. Consequently, it is unlikely that low DO is having measurable effects on populations of these fish species at present.

To evaluate the effects of lowered DO in the presence of pulp mill effluent on benthic invertebrates, an experiment was undertaken in which a commonly-occuring mayfly in the Northern Rivers (Baetis tricaudatus) was exposed to low DO concentrations (5 mg/L) and 1% treated pulp mill effluent at 4.5oC (Lowell and Culp 1996). The low DO level (5 mg/L) clearly stressed the mayflies leading to altered positioning behaviour, reduced feeding rate and decreased survival. The presence of the effluent had either no or a positive (i.e., increased feeding rate) effect. While 5 mg/L DO is generally not observed in the mainstem of the Athabasca River, the fact that mayflies live at or in the surface layers of the riverbed where DO concentrations are less than in the water column suggests DO concentrations in the rivers could already be at levels that could have chronic effects on these animals at localized sites.

7.4 CONCLUSIONS

During winter ice cover, the Athabasca River experiences DO concentrations less than saturation for its entire length downstream of Hinton (except immediately downstream of Grand Rapids). DO sag and recovery zones are observed downstream of the Weldwood of Canada Ltd. discharge in most winters and occasionally below Millar Western Pulp Ltd. DO concentrations less than the Alberta Surface Water Quality Objective (Alberta Environment 1977) of 5 mg/L DO do not routinely occur in the mainstem of the Athabasca River although the very occasional DO concentration of < 5 mg/L has been observed in near-shore areas or zones where effluent mixing was not complete. Experimental evidence that larval development of fall or winter spawning fish species can be delayed at 3 mg/L DO (mountain whitefish and bull trout) and possibly 6 mg/L (burbot) and that feeding rate and survival of the mayfly Baetis tricaudatus is reduced at 5 mg/L DO indicates a need for a more conservative DO objective. Given the fact that mayflies and the early life stages of fish live at or in the surface layers of the riverbed and that DO concentrations can differ by 3 mg/L DO between the water column and the sediment-water interface (Chapman 1986), water-column DO concentrations of 6-9 mg/L would be needed to protect these organisms. While detailed investigations of egg incubation and early rearing habitat for fish in the Northern Rivers were not undertaken, it is likely that the sites of egg incubation which experience lowered DO are not extensive and represent negligible quantities of the known and suspected incubation and early rearing habitat for bull trout, mountain whitefish and burbot in the Northern River basins. Consequently, it is unlikely that low DO is having measurable effects on populations of these fish species at present.

In the case of the Wapiti, Smoky, Peace and Slave Rivers, DO concentrations less than the 5 mg/L objective have never been observed. However, since mountain whitefish, bull trout and burbot also spawn in these systems, the more conservation objective proposed for the Athabasca River should also be applied to these systems.

The ability to accurately model DO concentrations in the Northern River, particularly the Athabasca River where winter DO concentrations regularly approach 7-8 mg/L, needs to be further refined to address: (1) short-term compliance needs (i.e., predicting DO levels during the upcoming winter), and (2) long-term basin management (i.e., scenario investigation with respect to changing industrial operations).

CHAPTER 8.0
SCIENTIFIC AND MANAGEMENT RECOMMENDATIONS

8.0 SCIENTIFIC AND MANAGEMENT RECOMMENDATIONS

8.1 MONITORING, DATA HANDLING AND REPORTING

- Regular monitoring and reporting of BOD5 from sewage treatment plants should be license requirements. Some of these larger sewage treatment plants, such as Fort McMurray, have BOD5 loads approaching that of pulp mills in the basins. Yet under the 1993 Alberta Environmental Protection and Enhancement Act, operators of continuously-discharging sewage treatments plants need only report exceedances (within 24 h) to Alberta Environmental Protection.

- Compliance with sampling and analytical procedures should be mandatory for all licensed dischargers. Demonstration of QA/QC for sampling and analytical procedures should be a license requirement and conducted at regular intervals. While all licenses stipulate that sample analysis must be conducted following the latest edition of Standard Methods for the Examination of Water and Waste Water (APHA 1995), some samples have been analyzed incorrectly (e.g., some BOD5 samples) and other methodologies (e.g., for BODu analysis) vary between laboratories.

- Provisions are needed to ensure training of certified operators to measure (and record) flows and discharge volumes and for enforcement of reporting requirements. At present, sewage treatment plant operators often supply missing, unreliable and/or ambiguous discharge data that then become incorporated in effluent databases (e.g., the Towns of Peace River, Barrhead and Wabasca have not reported reliable flow data). Reporting proper discharge data should be a license requirement.

- A properly-maintained central database should be established for: (a) effluent monitoring data (discharge and water quality parameters for all industries and municipalities with licensed monitoring requirements), and (b) environmental data collected by industries. These databases should be linked with the provincial surface-water quality database.

- Concern has been raised about DO concentrations in mixing zones. DO concentrations in mixing zones have never been explicitly studied although the Alberta Environmental Protection winter water quality surveys usually sample from both banks in reaches of effluent mixing. At low flow conditions, effluents to the Athabasca and Wapiti River are usually fully mixed by approximately 10 km downstream of the outfall. Since there have been no reports of impairment to fish in the mixing zones, further field work on mixing zones with respect of DO conditions is not recommended at this time.

- DO monitoring and modelling must be more closely tied to the distribution of fish and fish habitat and fish DO requirements.

8.2 DO MODELLING

8.2.1 Modelling Deficiencies

- Modelling goals need to be clearly defined. There appear to be two goals with respect to DO modelling in the Northern River basins: (1) short-term compliance assessments (i.e., predicting DO levels during the upcoming winter), and (2) long-term basin management (i.e., establishing license requirements with respect to changing industrial operations). Dynamic models (i.e., allowing for temporal and downstream variability in DO) may be better suited for addressing the short-term goal because early DO winter data could be used in predicting DO concentrations during late winter. Modelling for long-term basin management focuses on average or low-flow conditions and, hence, could be accomplished using a deterministic approach. For both approaches, a probabilistic model should be employed so as to allow assessment of the effect of variances in model input parameters on the confidence of the model predictions.

- Implementation of a dynamic model such as WASP (Water Quality Analysis Simulation Program) will address questions regarding temporal variability in the decrease in DO in the Athabasca River with distance (i.e., the changing relationship between upstream and downstream DO concentrations as the winter progresses). However, basic issues such as validating the ice-cover Leopold-Maddock coefficients used in calculating reach velocities (see Section 8.2.2) need to be resolved before more complex modelling is attempted. If WASP or any other DO simulation model is implemented, the model rates established and validated by Chambers et al. (1996) should be employed rather than calibration values.

- Concerns about DO concentrations in mixing zones could be addressed by moving to a model capable of 2-dimensional simulation (i.e., changes across the channel as well as longitudinally down the channel). However, there are currently only limited data on DO concentrations within mixing zones.

- Modelling of temporal DO patterns in the Athabasca River and the cumulative impacts on populations of mountain whitefish, bull trout and burbot should be attempted.

- Modelling of effluent discharge timing and seasonal DO sagging in the Athabasca River should be conducted whenever industrial operations change or unusually low winter flows are forecast, and a schedule developed to minimize increases in chemical and biological oxygen demand during late winter.

- Modelling needs to be undertaken by one group and independently reviewed by another group with modelling expertise to validate the assumptions and subjectivity that comes into play when modelling complex systems with parameter-rich (sometimes data-poor) models.

8.2.2 Data Deficiencies

- Additional measures of STP BOD_5 decay rates and BOD_u:BOD_5 ratios are required to verify the values currently used in the modelling. Currently this information is limited to data from Grande Prairie STP on one date.

- Cross-channel variability in SOD should be examined and the relationship between sedimentation and SOD should be assessed, particularly below mill outfalls and tributary inflows.

- Ice-cover Leopold-Maddock coefficients, which are used to establish reach velocities and to convert areal SOD to volumetric SOD rates, should be re-evaluated for discharges similar to the long-term average discharge at Hinton. Comparisons of time-of-travel by Thompson and Fitch (1989) and Andres et al. (1989) showed discrepancies particularily in the reach downstream of Hinton (Chambers et al. 1996). An additional under-ice time of travel study should be conducted to verify the results of Andres et al. (1989) and provide further data for re-assessing the ice-cover Leopold Maddock coefficients.

- Temperature correction coefficients for correcting laboratory measurements of BOD decay made at 20oC to the river temperature of 0oC in winter must be validated.

- Photosynthetic rates below ice and snow cover of differing thicknesses should be measured during years when this is deemed significant and the influence of this parameter on DO modelling should be evaluated.

- With respect to two-dimensional modelling (i.e., changes in DO over time and with distance downstream), little or no temporal data exist on parameters such as SOD, the size of open-water leads, photosynthetic rates (both temporally and diel), and BOD5 sedimentation.

- The use of "balanced", "estimated" or "measured" river and tributary flows should be standardized. What discharge should be used for tributaries that are not gauged? How is discharge calculated on the mainstem between gauged stations?

- Data are not available on groundwater inputs, diffuse loading, the size of open-water leads, nitrification (i.e., nitrogenous oxygen demand), and the applicability of SOD rates measured near shore to the entire channel.

- The concentration of DO upstream of Hinton is an important factor determining downstream concentrations in the Athabasca River. Between 1990 and 1993, DO concentrations in the Athabasca River upstream of Hinton ranged from 11.5 to 12.5 mg/L approximately 3-4 weeks after freeze-up. Concern about forecasting DO concentrations upstream of Hinton could be resolved by recognizing that modelling for: (1) long-term basin management must focus on average or worst-case scenarios (thereby eliminating the need to predict headwater DO concentrations for any particular year), and (2) short-term compliance assessments could be initiated in early winter using headwater DO concentrations measured in early winter (December or January) and average winter variance of headwater DO, or could incorporate a model relating headwater DO concentration to ice development.

8.3 RESEARCH

- In situ measurements of DO levels in the substratum during winter and their relationship to water-column DO concentrations are necessary to assess the DO status of fish and benthic invertebrate habitat and to predict substratum DO concentrations from the more routine measurements of water-column values.

- Studies of the combined effects of effluent and low DO levels should be expanded to include other fish species and important benthic invertebrates and to assess how impacts may be modified by differences in developmental stage or in acclimation time to low DO levels. In fish, contaminant-DO interactions should be examined, specifically the relationship between various hormonal and enzyme induction indicators of stress and seasonally low DO.

- Sedimentation rates should be measured below all mills to determine if settling rates are the same for different effluent types. Also, a determination of whether the sedimentation rates measured for all material (organic and inorganic) applies to only oxygen-consuming material is needed.

- The cause of elevated SOD rates below pulp mill discharges needs to be established. These higher SOD rates may be due to organic carbon loading or enhanced periphyton growth due to nutrient loading from pulp mills.

- In situ bioassays with eggs of mountain whitefish, bull trout and burbot should be conducted at key sites in the Athabasca River in conjunction with measurements of DO, BOD5, contaminant occurrence and effects, and ice cover effects. In addition, laboratory studies are required to determine a dose-dependent relationship between individual embryonic development stages and DO concentration for each of the major fish species. This work should include incubation trials at 0 to 1oC to more closely simulate natural winter temperature regimes.

8.4 WATER QUALITY AND EFFLUENT GUIDELINES

- Effluent permit limits should be assessed and based on environmental effects rather than technology design standards. The 3 kg BOD_5/air-dried-tonne limit for most pulp mills and the 25 mg/L BOD_5 limit for most municipal discharge permits is a technology-based limit.

- The Towns of Peace River, Fort Smith and Fort Chipewyan have continuous sewage discharges that often exceed the permit limit of 25 mg/L BOD_5. In the case of Peace River and

Fort Smith, these high discharges may not have biological consequences due to the large volumes of water in the Peace and Slave rivers. In addition, 26 periodic municipal dischargers (i.e., discharge from wastewater stabilization lagoons) exceeded the 25 mg/L BOD_5 limit (based on 1990-1993 data). An assessment of the environmental impacts of these exceedances is recommended.

- Regulatory standards for DO need to be reviewed to ensure that they are consistent with the minimal requirements known to be important for the native fishes of the Norther River basins. Laboratory studies on effects of lowered DO levels (3 mg/L) at low temperature (2-3 oC) showed that mountain whitefish eggs took longer to hatch and bull trout alevins were less well developed than at higher DO concentrations. DO concentrations of 6 mg/L may also extend the time required to hatch by some burbot. The commonly-occuring mayfly in the Northern Rivers (Baetis tricaudatus) was also found to have decreased survival and reduced feeding rates at a DO concentration of 5 mg/L. Given the fact that mayflies and the early life stages of fish live at or in the surface layers of the riverbed and that DO concentrations can differ by 3 mg/L DO between the water column and the sediment-water interface (Chapman 1986), DO concentrations in the Athabasca River could already be at levels that could have chronic effects on these animals at localized sites. Based on the fact that many fall-spawning fish species in the Northern River basins are in the salmonid family, the more conservative Canadian Water Quality Guideline (CCREM 1987) of 6.5 mg/L DO for salmonids is recommended as a policy-based guideline to be used in setting effluent license conditions for periods of ice-cover.

CHAPTER 9.0
REFERENCES

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APPENDIX A

Appendix A Means, standard errors and sample size (n) for effluent discharge, BOD$_5$ concentrations and BOD$_5$ loads for mills and municipalities. Mill data from *Northdat* (McCubbin and AGRA Earth and Environmental 1995). Municipal data from a database of D. Prince and Stanley (University of Alberta, Department of Civil Engineering) unless otherwise indicated. Only municipalities with continuous discharge have discharge data. Loads were calculated as the product of discharge and BOD$_5$ concentration for samples collected on the same day. Blank cells indicate data not available.

Mills

Mill	Discharge (m^3/s)			BOD Load (kg/d)		
	mean	standard error	n	mean	standard error	n
Weldwood of Canada Ltd	106557	407	1479	2309	25	1433
Alberta Newsprint Company	15536	90	1287	161	6	1256
Millar Western Pulp Ltd.	12041	61	1473	768	14	1469
Slave Lake Pulp Corp.	4698	42	1154	654	25	1140
Alberta Forest Industries Inc.	67826	804	180	936	100	177
Weyerhaeuser Canada Ltd.	58599	288	1438	2066	32	1413
Daishowa-Marubeni Inernational Ltd.	61044	320	1279	1565	35	1248

Municipalities

Municipality	Measurement Dates	Discharge (m^3/d)			BOD Concentration (mg/L)			BOD Load (kg/d)		
		mean	S.E.	n	mean	S.E.	n	mean	S.E.	n
Anzac	May88				22.1		1			
Athabasca	Jan90-Mar93[1]	952	10	39	14.6	1.7	39	13.8	1.6	39
	May83-May9[2]				16.8	2.2	18			
	Mar89-Mar93[2]	978	42	6	31.9	19.1	5	28.8	16.2	5
Barrhead	Oct82-Apr91				40.8	11.4	15			
	Jan90-Mar93[1]				18.1	1.5	38			
Beaverlodge	Nov82-Oct86				22.1	4.3	9			
Berwyn	Apr84-Oct84				7.4	0.4	2			
Blue Ridge	Oct84				16.1		1			
Bluesky	Sep83-Sep84				9.1	7.0	2			
Boyle	Oct82-Oct85				13.5	4.9	3			
Clairmont	May84				126		1			
Coutts	Oct85-Oct86				8.3	5.3	2			
Cynthia	Apr85-Oct85				26.9	8.9	2			
Debolt	Apr84-Aug87				37.1	8.2	3			
Desmarias	Aug83-Jul86				296	290	4			
Eaglesham	Nov82-Nov86				53.5	14.2	6			
Edson	Jan90-Mar93[1]	3954	312	34	13.3	1.0	39	58.6	8.4	34
	Jul82-May92				15.6	2.7	12			
Entwistle	Oct83-Aug87				51.9	10.6	12			
Evansburg	Oct82-Sep85				24.6	11.1	3			
Fairview	May83-Apr85				14.4	6.4	4			
Falher	Apr83-Mar84				13.8	8.8	2			
Faust	Oct83-Oct85				4.7	1.1	3			
Fawcett	Jul84				54.0		1			
Fort Chipewyan	Apr84				14.0		1			
Fort McMurray	Jan90-Mar93[1]	14000	393	17	20.4	0.8	39	314	19.6	17
	Jun83-Sep91				17.2	2.9	8			
	Jan89-Mar93[2]	14287	1397	5	23.7	12.1	5	182.8	63.8	4

Fort Smith	Jan91-Dec93	480	2	36	100.5	7.0	37	49.2	4.4	25
Fort Vermilion	Oct83-May88				16.8	6.5	4			
Fox Creek	Apr83-Oct85				18.8	6.2	5			
Girouxville	May85				22.6		1			
Grande Cache	Jan90-Mar93[1]	2032	59	39	3.8	0.2	39	7.8	0.4	39
	Jul83-Jan92				8.9	1.2	13			
GrandePrairie	Jan90-Mar93[1]	10728	382	39	8.6	0.6	39	92.6	7.3	39
	Jan85-Apr91				33.3	2.6	73			
	Feb89-Mar92[2]	17712	1581	4	5.6	3.2	3	87.5	39.6	3
Grassland	Oct83-May92				20.2	11.9	4			
Grimshaw	Sep82-Nov86				59.6	21.7	3			
Grouard	Oct84-Oct85				5.3	1.4	2			
High Level	Oct83-Oct85				23.8	20.4	4			
High Prairie	May84				4.1		1			
Hines Creek	Nov82-May85				9.5	4.2	3			
Hythe	Oct82-Oct86				32.9	16.0	6			
Jarvie	Apr83				52.5		1			
Jasper	Dec91-Dec92[1]	3948	272	13	19.7	3.5	11	82.7	21.3	11
	Oct90-Aug91				55.6	32.8	2			
Lac La Biche	Jan90-Mar93[1]	1425	78	35	24.8	2.1	38	35.7	3.8	35
	Jan84-Feb92				32.5	6.2	18			
La Glace	Oct82-Oct84				31.6	14.1	3			
Loon Lake	May84				3.6		1			
Manning	Jan91-Dec92[1]	487	14	24	19.6	1.4	31	9.6	0.7	24
	Jun83-Oct90				18.6	4.2	8			
Mayerthorpe	Apr83				10.8		1			
Mclennan	May83-Oct85				5.7	1.6	4			
Nampa	Aug83				15.1		1			
Neerlandia	May83-Oct85				42.7	11.4	4			
Peace River										
Peace River Correctional Institute	Jan90-Mar93[1]	286	21	37	6.0	0.5	39	1.8	0.2	37

Pickardville	Apr83-Apr85				99.1	30.6	3			
Plamondon	Apr85				34.3		1			
Rainbow Lake	Oct83-Oct84				12.6	3.5	3			
Robb	Jun82				46.0		1			
Rycroft	Apr83-Sep84				10.3	6.9	2			
Sangudo	Oct82-Oct84				15.0	1.7	3			
Sexsmith	Apr84-Oct85				36.9	25.6	2			
Slave Lake	Jan91-Mar93[1]	2729	38	25	15.7	1.5	36	49.3	5.0	25
	Jul82-Jul92				21.1	3.2	15			
	Jan89-Mar93[2]	2501	13	4	17.7	2.4	7	50.9	5.4	4
Spirit River	Sep82-Oct86				45.2	26.1	3			
Swan Hills	Nov82-Oct84				27.3	10.7	4			
Triple L Mobile Home	May84-Nov87				27.5	4.7	3			
Valleyview	Sep82-Oct85				9.8	0.7	3			
Wabasca	Jan89-Jan93[1]	245	28	35	5.9	0.5	50	1.2	0.2	50
	Jul85-Jul92				18.1	4.7	5			
Wanham	Nov83-Oct86				21.8	4.5	4			
Wembley	Sep82-May85				15.5	2.7	4			
Westlock	Oct82-May92				27.8	9.1	11			
Whitecourt	Jan90-Mar93[1]	3417	37	39	9.8	1.0	39	34.1	3.7	39
	Aug82-Nov91				12.8	2.4	12			
	Jan89-Mar93[2]	3288	106	5	14.1	3.1	6	51.3	10.9	5
Wildwood	Oct82				11.5		1			
Woking	Jul84				20.6		1			
Worsley	Sep84-May85				5.9	2.4	2			
Zama City	Oct83-Apr87				47.3	23.6	4			

[1] Data from the NRBS Municipal and Non-Pulp Mill Industrial Effluents Database (Sentar Consultants Ltd. 1995)

[2] Data from the Alberta Environment winter water quality surveys from 1989 to 1993.

The Northern River Basins Study was established to examine the relationship between industrial, municipal, agricultural and other development and the Peace, Athabasca and Slave river basins.

Synthesis Report

Over four and one half years, about 150 projects, or "mini studies" were contracted by the Study under eight component categories including contaminants, drinking water, nutrients, traditional knowledge, hydrology/hydraulics, synthesis and modelling, food chain and other river uses. The results of these projects, and other work and analyses conducted by the Study are provided in a series of synthesis reports.

This Synthesis Report documents the scientific findings and scientific recommendations of one of these components groups. This Synthesis Report is one of a series of documents which make up the North River Basins Study's final report. A separate document, the Final Report, provides further discussion on a number of scientific and river management issues, and outlines the Study Board's recommendations to the Ministers. Project reports, synthesis reports, the Final Report and other NRBS documents are available to the public and to other interested parties.