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CYP1A INDUCTION AND BLUE SAC DISEASE IN EARLY LIFE STAGES OF WHITE SUCKERS (*Catostomus commersoni*) EXPOSED TO OIL SANDS

Maria V. Colavecchia[1,2], Peter V. Hodson[2], Joanne L. Parrott[1]

[1]Environment Canada, Science and Technology Branch, Burlington, Ontario, Canada
[2]Queen's University, School of Environmental Studies, Kingston, Ontario, Canada

The objectives of this study were to evaluate the influence of natural oil sands on the early developmental stages of white sucker (Catostomus commersoni) *and to determine whether biochemical responses in this species were similar to native fish caught in the Athabasca Oil Sands area. Early life stage (ELS) sediment toxicity tests were conducted using controls, reference sediments, natural oil sands, and industrially contaminated (wastewater pond) sediments collected from sites along the Athabasca River, Alberta (Canada). Eggs and larvae were observed for mortality, hatching, deformities, growth, and cytochrome P-4501A (CYP1A) activity using immunohistochemistry. E-Nat-, S-Nat-, and wastewater pond sediment-exposed groups showed significant premature hatching, reduced growth, and exposure-dependent increases in ELS mortality and larval malformations relative to controls. The most common larval deformities included edemas (pericardial, yolk sac, and subepidermal), hemorrhages, and spinal defects. Juveniles exposed to oil sands and wastewater pond sediments (96 h) demonstrated significantly increased 7-ethoxyresorufin–O-deethylase (EROD) activity (30- to 50-fold) as compared to controls. Reference sediment-exposed groups and water controls demonstrated reliable embryo and larval survival, minimal malformations, and negligible CYP1A staining. These observed signs of blue sac disease (ELS mortality, malformations, growth reductions, CYP1A activity induction) may produce deleterious reproductive effects in natural fish populations exposed to oil sands mixtures.*

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Address correspondence to Maria V. Colavecchia, Environment Canada, Science and Technology Branch, Burlington, Ontario, L7R 4A6, Canada. E-mail: Maria.Colavecchia@ec.gc.ca

INTRODUCTION

Oil sands mining is a large and growing industry in the Athabasca region of northern Alberta, Canada. The Athabasca Oil Sands is the largest of 4 oil deposits in the province with an estimated 1.7 trillion barrels of bitumen (Alberta Department of Energy, 1995). Bitumen is a naturally weathered, heavy crude oil composed of a complex mixture of hydrocarbons, heteroorganics, and metals. Headley et al. (2001) recently characterized the degree of natural polyaromatic hydrocarbons (PAHs) in this region and showed that tributary sediments contain significant levels of PAHs, particularly alkyl-substituted PAHs (0.01 to 34.7 μg/g). Surface waters in the Athabasca River basin contain PAHs and naphthenic acids (NAs) derived naturally from the erosion of bitumen deposits along the banks of rivers and from riverbeds. The main chemical compounds in semipermeable membrane device (SPMD) dialysates from surface waters in this region are PAHs, alkyl-PAHs, NAs, benzothiophenes, and methyl carbazoles (Parrott et al., 1996). Increased 7-ethoxyresorufin *O*-deethylase (EROD) activity in cultured fish cells exposed to these extracts indicates that fish are exposed to naturally occurring oil sands related compounds (OSRCs) that are capable of inducing mixed-function oxygenase enzyme (MFO) activity (Parrott et al., 1996).

There are also OSRCs originating from oil sands extraction activities. Syncrude Canada Ltd. and Suncor Energy, recover oil adjacent to the Athabasca River, producing large volumes of wastewaters (tailings). Researchers have assessed several endpoints in native yellow perch (*Perca flavescens*) stocked in tailings ponds, and found elevated EROD activity and bile PAHs metabolites (van den Heuvel et al., 1999). In addition, exposed perch exhibited increased gill pathologies and skin lesions that were correlated with the concentrations of OSRCs (van den Heuvel et al., 2000). As industries expand production and open new mines, concerns related to the potential detrimental impacts on aquatic ecosystems are growing. There is a need to determine the possible effects arising from OSRCs leaching from sediments, from both anthropogenic and natural source areas.

While the toxicity of tailings waters was documented, few data exist on the effects of natural oil sands on indigenous species. Recent studies showed altered biochemical and reproductive responses in native fish species residing in the Athabasca oil sands relative to reference fish (Tetreault et al., 2003a). Native slimy sculpin (*Cottus cognatus*) and pearl dace (*Semotilus margarita*) residing within natural oil sands showed reductions in steroid production and increased EROD activity relative to reference areas. Wild adult longnose suckers (*Catostomus catostomus*) captured in oil sands areas demonstrated a 15-fold increase in EROD activity as compared to reference fish (Parrott et al., 1999). Although researchers did not find effects on body condition, these studies provided valuable baseline information important for future environmental monitoring in this region.

Early life stages (ELS) of fish exposed to weathered crude oils (Couillard, 2002; Carls et al., 1999; Marty et al., 1997a, 1997b), oil sand extracts (Rhodes et al., 2005), and natural oil sands (Colavecchia et al., 2004) demonstrated significant toxicological responses that have been linked to PAHs exposure. Fathead minnows (*Pimephales promelas*) exposed to natural oil sands and wastewater sediments showed exposure-related increases in ELS mortality, larval malformations, and reduced size. Differential toxicity among sites was related to sediment PAHs concentration and composition, specifically alkyl-substituted PAHs (Colavecchia et al., 2004). In general, sediment PAHs in natural oil sands (250–360 μg/g TPAH) were predominantly composed of alkylated derivatives of phenanthrene/anthracene, fluoranthene/pyrene, and benz[a]anthracene/chrysene. High concentrations of alkylated benz[a]anthracene/chrysene and benzofluoranthene/pyrene compounds were detected in the refinery wastewater pond sediments (1300 μg/g TPAH). Since little is known about the toxicity of alkylated PAHs to the ELS of teleosts (NRC, 1985), it is important to assess whether PAHs and other OSRCs are bioavailable and have the potential to produce effects in fish.

The objectives of this study were to assess the effects of OSRCs (both naturally occurring and those due to anthropogenic inputs) on the ELS of white suckers (*Catostomus commersoni*). The wide natural distributions of this species make it an ecologically relevant species for many areas of North America (Nelson & Paetz, 1992). Preliminary assessments of native adult suckers in the Athabasca Oil Sands region indicate this species was exposed to naturally occurring OSRCs, with reduced gonad size as compared to upstream fish (Parrott et al., 1999). Impacts on ELS were assessed in terms of hatching success, time to hatch, larval development, growth, and survival. Several studies demonstrated EROD induction in fish following lab exposure to PAHs and crude oils (van der Weiden, 1994; Marty et al., 1997b). A second objective was to evaluate whether a laboratory exposure of juvenile fish to oil sands sediments could produce biochemical responses (EROD induction) similar to those of fish caught in the Athabasca Oil Sands area.

MATERIALS AND METHODS

Sediment Collection

In October 2001, surface sediments were collected from two tributaries of the Athabasca River, namely, the Ells River and the Steepbank River, Alberta, Canada (Figure 1). In each of these tributaries, river sediments were collected from downstream (natural) and upstream (reference) sites. The downstream samples were collected within the oil sands deposit where there are natural PAHs inputs (E-Nat, 57°16.01′N/111°42.51′W, and S-Nat, 57°1′23″N/111°28′30″W), whereas the reference sediments were taken upstream, outside of the oil sands deposits (E-Ref, 57°13.52′N/111°53.15′W, and S-Ref, 56°55′40″N/111°13′56″W). In addition, sediments were collected from a refinery wastewater pond (WWP) located at an oil sands mining facility (Suncor Energy). This latter site is within the oil sands deposit and directly impacted by anthropogenic surface mining activities (Figure 1). More details on sediment sampling,

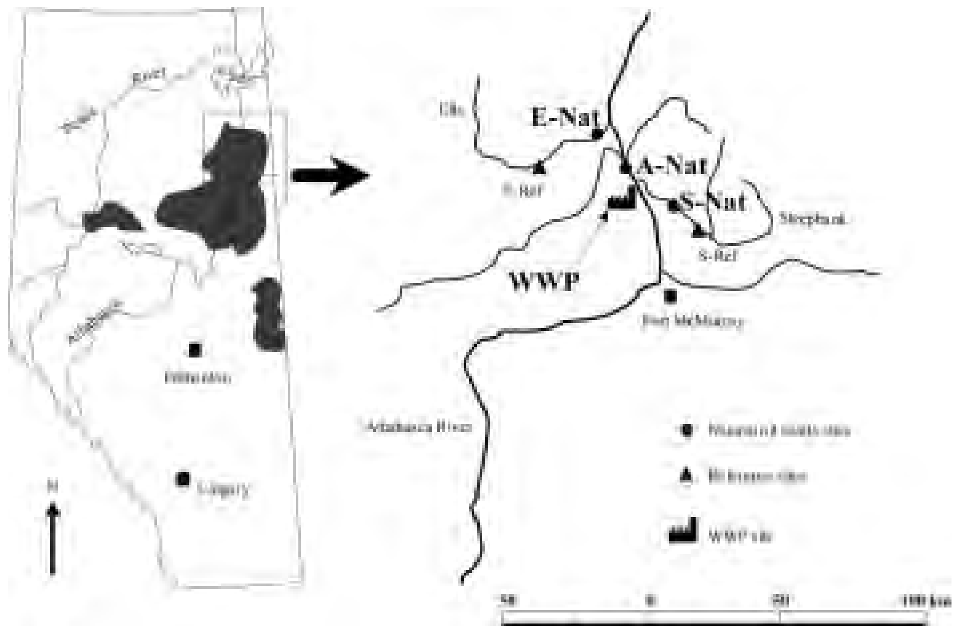

FIGURE 1. Map of rivers and study sites in the Athabasca oil sands area, in northern Alberta (Canada). Oil sands deposits are shaded. Sediment collection sites included the downstream (natural: E-Nat and S-Nat) and upstream (reference: E-Ref and S-Ref) reaches of the Ells and Steepbank Rivers. These areas lie within and outside the natural oil sand deposit, respectively. Sediments influenced by oil refining operations were also tested (WWP).

site descriptions, and sediment PAHs analyses are available in Colavecchia et al. (2004). In general, sediment samples were spiked with a deuterated PAHs standard mixture, solvent extracted, concentrated, and passed through silica gel cleanup columns. PAHs analyses were conducted using gas chromatography–mass spectrometry on final fractions containing the aromatic hydrocarbons. Total sediment PAHs concentrations (TPAH) and composition are summarized in Figure 2. Sediment TPAH concentrations from both reference sites were comparatively very low (0.03 μg/g for S-Ref and 2.4 μg/g for E-Ref), and many PAHs compounds were not detected in these sediments.

The concentration of each chemical in water (C_w) was estimated using the following equation;

$$C_w = C_s / K_{oc} \cdot f_{oc}$$

where C_s is the concentration of the chemical on sediment, K_{oc} is the organic normalized sorption coefficient, and f_{oc} is the weight fraction of organic carbon in the sediment (Table 1). K_{oc} values were obtained from MacKay et al. (1992). For compounds with no available literature value, K_{oc} values were calculated

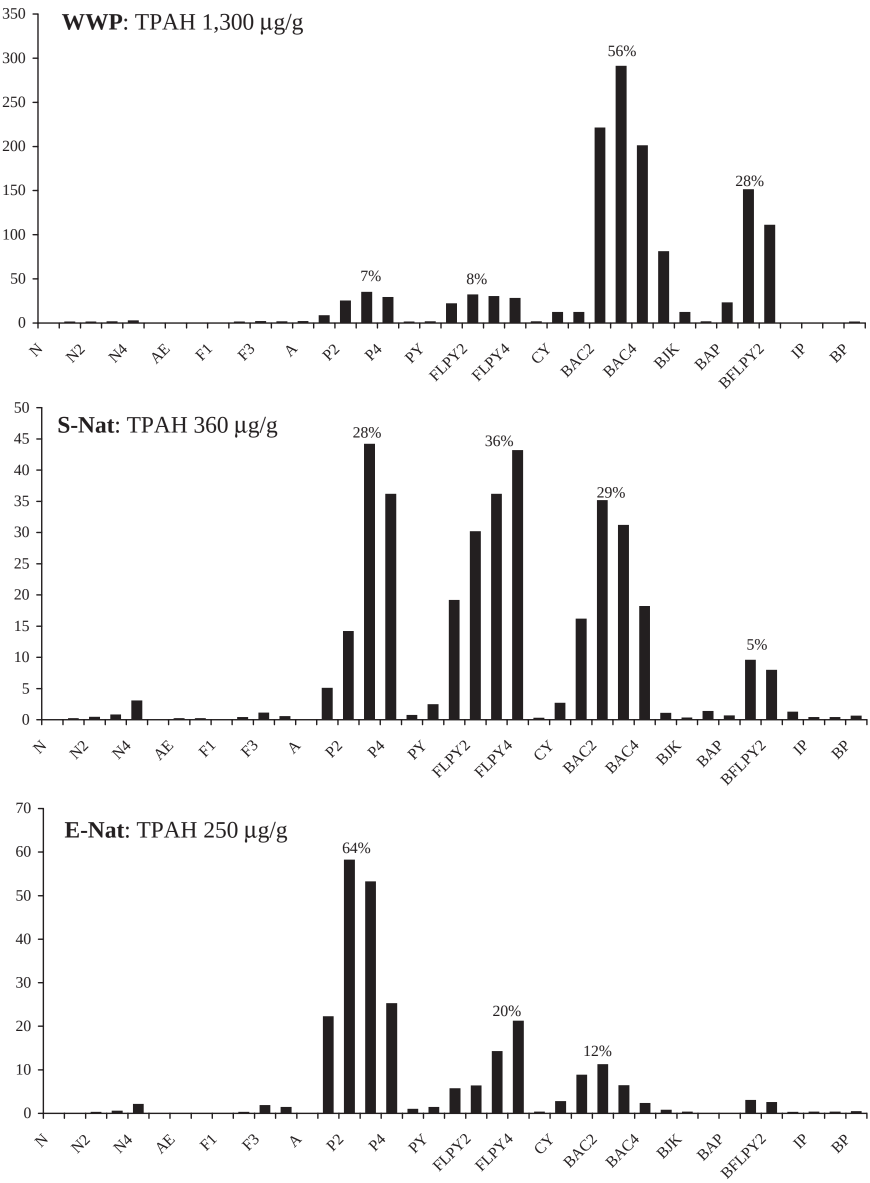

FIGURE 2. Concentrations of alkylated PAHs for sediments collected from the WWP and the downstream reaches of the Ells and Steepbank Rivers. The *y* axis refers to approximate concentration (µg/g). Note that the *y*-axis scales are not all the same. Abbreviations for analytes on the *x* axes are as follows: naphthalene (N), acenaphthene (AE), fluorene (F), anthracene (A), phenanthrene (P), pyrene (PY), fluoranthene/pyrene (FLPY), chrysene (CY), benz[a]anthracene/chrysene (BAC), benzo[j,k]fluoranthene (BJK), benzo[a]pyrene (BAP), benzofluoranthene/pyrene (BFLPY), indeno[1,2,3-cd]pyrene (IP), and benzo[g,h,i]perylene (BP). Values above the bars indicate the percentage of that alkyl group in relation to the TPAH concentration.

TABLE 1. Total Polycyclic Aromatic Hydrocarbon (TPAH) Concentrations in Sediments (C_s, ng/g) and Estimated Water Concentrations (C_w, ng/L) in Fish Exposures, with C_w Values are Based on the Highest Exposure Tested (25 g/L)

			WWP		E-Nat		S-Nat	
Compound	log K_{ow}[a]	log K_{oc}[b]	C_s	C_w	C_s	C_w	C_s	C_w
Naphthalene (N)	3.37	3.11	56	20	1	1	0	0
C1-Naphthalene (N1)	3.87	3.36	300	60	6	5	34	18
C2-Naphthalene (N2)	4.37	3.93	300	16	50	11	270	38
C3-Naphthalene (N3)	4.86	4.78[c]	430	3	340	11	620	12
C4-Naphthalene (N4)	5.55	5.46[c]	1600	3	1900	12	2900	12
Acenaphthylene (AC)	4.07	3.4	0	0	0	0	0	0
Acenaphthene (AE)	3.92	3.66	12	1	1	0	33	9
Fluorene (F)	4.18	4.15	110	4	4	1	24	2
C1-Fluorene (F1)	4.97	4.89[c]	19	0	20	0	0	0
C2-Fluorene (F2)	5.2	5.11[c]	330	1	75	1	210	2
C3-Fluorene (F3)	5.5	5.41[c]	750	1	1600	12	940	4
Phenanthrene (P)	4.57	4.36	510	10	1200	99	370	20
Anthracene (A)	4.54	4.42	770	13	0	0	0	0
C1-Phenanthrene/anthracene (P1)	5.14	5.05[c]	7300	30	22,000	371	4900	53
C2-Phenanthrene/anthracene (P2)	5.51	5.42[c]	24,000	42	58,000	418	14,000	64
C3-Phenanthrene/anthracene (P3)	6	5.9[c]	34,000	20	53,000	126	44,000	67
C4-Phenanthrene/anthracene (P4)	6.51	6.4[c]	28,000	5	25,000	19	36,000	17
Fluoranthene (FL)	5.22	4.58	350	4	760	38	560	18
Pyrene (PY)	5.18	4.92	510	3	1200	27	2300	33
C1-Fluoranthene/pyrene (FLPY1)	5.72	5.62[c]	21,000	23	5500	25	19,000	55
C2-Fluoranthene/pyrene (FLPY2)	5.72	5.62[c]	31,000	34	6100	28	30,000	87
C3-Fluoranthene/pyrene (FLPY3)	5.72	5.62[c]	29,000	32	14,000	64	36,000	104
C4-Fluoranthene/pyrene (FLPY4)	5.72	5.62[c]	27,000	30	21,000	95	43,000	125
Benz[a]anthracene (BA)	5.91	5.3	620	1	130	1	130	1
Chrysene (CY)	5.86	5.76[c]	11,000	9	2500	8	2500	5
C1-Benz[a]anthracene/chrysene (BAC1)	6.42	6.31[c]	11,000	2	8600	8	16,000	9
C2-Benz[a]anthracene/chrysene (BAC2)	6.88	6.76[c]	220,000	18	11,000	4	35,000	7
C3-Benz[a]anthracene/chrysene (BAC3)	7.44	7.31[c]	290,000	7	6200	1	31,000	2
C4-Benz[a]anthracene/chrysene (BAC4)	8	7.86[c]	200,000	1	2100	0	18,000	0
Benzo[b]fluoranthene (BB)	5.8	5.74	80,000	67	560	2	890	2
Benzo[j,k]fluoranthene (BJK)	6.84	5.74	11,000	9	110	0	160	0
Benzo[e]pyrene (BE)	6.44	7.2	530	0	11	0	1200	0
Benzo[a]pyrene (BAP)	6.04	6.74	22,000	2	22	0	500	0
C1-Benzofluoranthene/pyrene (BFLPY1)	6.28	6.17[c]	150,000	46	2800	4	9400	8
C2-Benzofluoranthene/pyrene (BFLPY2)	6.28	6.17[c]	110,000	34	2300	3	7800	6
Perylene (PYL)	6.5	6.39[c]	0	0	69	0	1100	1
Indeno[1,2,3-c,d]pyrene (IP)	6.72	6.61[c]	0	0	100	0	220	0
Dibenz[a,h]anthracene (DA)	6.5	6.52	0	0	81	0	210	0
Benzo[g,h,i]perylene (BP)	6.5	6.2	190	0	200	0	440	0
Total PAHs (TPAH)			1,300,000	550	250,000	1400	360,000	780

Note. Site abbreviations are noted in text and include: WWP, wastewater pond sediments (carbon content is 5.46%); E-Nat (carbon content is 1.32%) and S-Nat (carbon content is 2.07%), natural oil sands on the Ells and Steepbank Rivers, respectively.

[a]Reported values from MacKay et al. (1992) and Neff and Burns (1996)

[b]Reported values from MacKay et al. (1992)

[c]Estimated from $\log(K_{oc}) = 0.00028 + 0.983 \log(K_{ow})$ (Di Toro & McGrath, 2000). Cs values are reported from Colavecchia et al. (2004)

using the following equation; $\log(K_{oc}) = 0.00028 + 0.983 \log(K_{ow})$ (Di Toro & McGrath, 2000), where K_{ow} is the octanol/water partition coefficient. In general, estimated water concentrations ranges were 2–550 ng/L (WWP), 6–1400 ng/L (E-Nat) and 3–780 ng/L (S-Nat) for the exposure ranges tested in this study (Table 1).

ELS Collection and Fertilization

Adult white suckers were collected from a spawning run in the Sheridan Creek, a tributary to Rattray Marsh, Lake Ontario (43°51.7′E/79°60.1′N). Ripe fish were captured using a Smith–Root Type 15-B backpack electrofisher during April 2002. Males and females were separated and held in aerated coolers prior to gamete collection. Fish were anesthetized using a 1:10 clove oil:ethanol solution (40 mg/L, diluted in 20 L river water), and gametes were fertilized as described by McMaster et al. (1992). Upon arrival in the lab, river water was decanted and the eggs were rinsed five times with lab water. The water for all aspects of acclimatization and exposures was dechlorinated, charcoal-filtered, Burlington (ON, Canada) municipal water. Water hardness, conductivity, and pH were 130 mg/L as $CaCO_3$, 304 μS/cm, and 7.7, respectively.

ELS Exposure and Sampling Protocols

Standard protocols were modified for the 12-d fathead minnow ELS bioassay (Colavecchia et al., 2004) by starting sediment exposures with newly fertilized white sucker eggs less than 12 h postfertilization (hpf). Eggs and larvae were exposed for ~35 d, which included a 14-d embryonic exposure, followed by 21-d posthatch (21 dph) larval exposure. Eggs and larvae were maintained in a controlled incubator (15 ± 1°C) on a 16-h light (L):8-h dark (D) cycle. An incubation temperature of 15°C was selected, as this has been shown to produce maximum hatching success in wild white sucker eggs (McCormick et al., 1977).

Eggs (25 per container) were placed in glass Nitex mesh-bottomed cups (500 μm size), suspended 2 cm above the bottom of 1-L covered glass beakers. Egg cups were made from 12 cm high glass tubing (8 cm outer diameter, 7.5 cm inner diameter) and contained 500-μm-mesh Nitex screen bottoms. Two solid-glass rods with a diameter of 1 cm were attached horizontally with silicone to the bottom of each cup to displace them from the bottom of the beaker in order to facilitate water exchange during the exposure period. A high to low exposure gradient was developed in sediment:water ratios similar to those described by Oikari et al. (2002). Beakers contained varying amounts of sediments (25, 6.25, 1.56, 0.39, and 0.1 g), 1 L of overlaying lab water, and moderate aeration. Both sediments and water were renewed daily and sediments were allowed to equilibrate for 24 h before adding embryos and larvae. There were 85 sediment treatments (3 sites × 5 exposures × 5 replicates; 2 reference sites × 1 exposure × 5 replicates) and controls (water and fish, no sediment). Feeding of larvae started at 7 dph, and each beaker received a slurry of concentrated brine shrimp (*Artemia salina*) twice daily, providing ~10 μl of brine shrimp/larva, which was adjusted daily to account for remaining live larvae.

Dilution water pH, dissolved oxygen (DO), temperature, conductivity, and ammonia levels were measured twice weekly in all beakers before water changeover. Ammonia concentrations were estimated using a commercial freshwater ammonia (NH_3/NH_4) test kit (number 33A, Aquarium Pharmaceuticals, Mississauga, ON, Canada). The ranges for temperatures, DO, pH, conductivity, and ammonia in exposure waters were as follows: 14 to 16°C, 8.8 to 10.9 mg/L, 7.45 to 8.33, 0.16 to 0.34 μS/cm, and 0.05 to 1 ppm. There were no significant differences in water quality of dilution waters among treatments during the duration of the exposures.

For each beaker, the numbers of eggs and larvae that died or hatched were recorded daily. At hatching, the number of larvae that developed malformations was noted, and separate records were kept of the prevalence of edemas, hemorrhaging, and skeletal deformities (see Elonen et al., 1998, for representative photographs). Skeletal abnormalities included larvae with coiled or curved spinal columns. Multifocal hemorrhages (including hemostasis) were visible in several areas, including the trunk, yolk sac, pericardial, ocular, and cranial tissues. At hatch, subsamples (n = 5/group) of larvae were sampled for later histology and CYPIA protein induction using immunohistochemistry (data not shown). On d 35, remaining larvae were sacrificed and preserved larvae were blotted dry, weighed (±0.1 mg wet weight), and measured for total length (±10 m) using a Summasketch III digitizing tablet (Summagraphics).

Juvenile Fish Holding and Exposure Regime

Wild juvenile white suckers (~4 g) were collected in the summer of 2002 from the same area and using similar methods as already described. The fish were held in aerated coolers, transported to the laboratory (~ 4 h), and held for 48 h in aerated tanks at 15 ± 1°C supplied with continuously flowing lab water at a flow rate above 1 L/g fish/d.

During sediment exposures, 5 fish were placed in 20 L water to give a loading density of <1 g fish/L water. Aquaria were 25-L, black, high-density polyethylene plastic buckets lined with clear, food-grade polyethylene bags (3 mil; Apache Plastic, Burlington, ON). Aquaria were prepared with 20 L dilution water, and sediments were added at low (0.002 g wet sediments/20 L) to high rates (588.215 g wet sediments/20 L). There were 39 sediment treatments (E-Nat and S-Nat sites × 10 exposures/each; 1 WWP site × 17 exposures; E-Ref and S-Ref sites × 1 high exposure/each), and additional aquaria were maintained for negative controls (water and fish only) and positive controls (10 μg/L of β-naphthoflavone [BNF], 10 mg/L MeOH, Sigma). Suspended particulates and sediments were allowed to settle for 24 h before adding fish to each tank. Sediments, water, and solutions were renewed daily and gently aerated throughout the experiment. All buckets were covered and housed in a temperature- and light-controlled water bath (15 ± 1°C, 16-h L:8-h D photoperiod cycle). Water quality was monitored daily before water changeover, and mean (±SD) values were: temperature 15.5 ± 0.5°C, pH 7.59 ± 0.65, specific conductance 291 μS/cm^2 ± 40, and DO 9.89 ± 0.21 mg/L.

Fish were not fed, and there was negligible mortality over the duration of the experiment.

Juvenile Fish Sampling and EROD Assay

At 96 h, fish were anesthetized in MS222 (100 mg/L, Sigma), weighed, measured, and then sacrificed by spinal severance. Livers and gallbladders were removed, placed in separate 2-ml cryogenic vials (Fisher Scientific), and immediately quick-frozen in liquid nitrogen before storage at −80°C.

All liver samples were assayed for 7-ethoxyresorufin–*O*-deethylase (EROD) activity by a kinetic fluorometry assay and total protein by a colorimetric assay as outlined by Hodson et al. (1996). The postmitochondrial supernatant (S9) fractions were prepared the morning they were assayed for EROD activity and total protein content. Livers were homogenized in 500 µl HEPES-KCl grinding buffer (0.15 *M* KCl, 0.02 *M* HEPES, pH 7.5). All samples were analyzed in triplicate in 96-well polystyrene tissue culture microplates (Corning Costar 3585, Fisher Scientific). The fluorescence of the product, resorufin, was measured with a spectrofluorometer (CytoFluor 2300 Plate Reader, PerSeptive Biosystems) equipped with excitation (530 nm) and emission filters (590 nm). Resorufin standards and external (positive and negative) controls were assayed with the S9 fractions. Rates of specific enzyme activity were calculated by measuring the slope of curves relating fluorescence to time, resorufin standard curves, and measured protein concentrations. The S9 protein concentrations were measured against bovine serum albumin as a standard with the BIORAD colorimetric assay (Bio-Rad) and with a VersaMax microplate spectrophotometer (Molecular Devices). Final values were expressed as specific molar activity, that is, EROD activity in picomoles per minute per milligram of protein (pmol resorufin/min/mg protein).

Statistical Analysis

ELS toxicity data were expressed as arithmetic means ± standard errors of the mean, with five replicates per treatment. Mortality and deformity responses for reference-exposed (S-Ref and E-Ref) and water control replicates were analyzed by two-way analysis of variance (ANOVA) and were pooled and averaged for data analysis. Egg mortality was the cumulative number of embryos that died prior to hatch and included incomplete hatches. Larval mortality refers to the cumulative number of larvae that died from hatch to the termination of exposure (21 dph). Mortality and malformation data in each replicate were converted to percent mortality and prevalence before statistical analysis. Threshold exposures were defined by the no-observable-effect concentration (NOEC) to lowest-observable-effect concentrations (LOEC) range. Where parametric assumptions of normality and homogeneity of variance could not be met by logarithmic transformation, the Kruskal–Wallis nonparametric statistic was used. Means were compared by Tukey's multiple comparison methods, followed by pairwise Dunnett's *t*-test. EROD data were log transformed, and for each treatment the 95% confidence limits about the geometric mean were calculated by taking the antilog of both parameters. The median (50% response) effective exposures (EC50) for each site were calculated using SigmaPlot 6.0 (San Rafael, CA), and all statistical analyses were performed using SYSTAT 10.0 (Evanston, IL). A p value ≤.05 was considered significant for all statistical tests.

RESULTS

Hatching Success

Control and reference sediment-exposed eggs demonstrated >80% hatch across replicates within 18 to 19 d. Hatching success was good (81.8 ± 3.3%) among control embryos (exposed to charcoal-filtered, dechlorinated, Burlington city water), and total larval mortality did not exceed 5% (1.8 ± 1.8%). Egg mortality was low among reference sediment-exposed eggs (15.7 ± 2.9% for S-Ref, and 19.1 ± 2.2% for E-Ref), and total larval mortality did not exceed 10% (4.9. ± 2.0% for S-Ref, and 7.0 ± 3.2% for E-Ref). There were no statistically significant differences between control and reference sediment-exposed groups in hatching success, time to hatch, and larval survival.

Abnormal embryo development and reduced movements were observed in some E-Nat-, S-Nat-, and WWP-exposed eggs (data not shown). These abnormalities included edemas, hemorrhages, and eye alterations. In contrast, control and reference sediment-exposed embryos displayed vigorous movements within the chorion and no visible malformations. E-Nat and S-Nat sediments produced significant exposure-dependent increases in egg mortality (Figure 3a), at and above thresholds of 1.5 and 6.2 g/L (E-Nat and S-Nat, respectively; Table 2). Eggs exposed to WWP sediments showed significant exposure-related increases in mortality at and above a threshold of 6.2 g/L (Figure 3a and Table 2).

The time to hatch (TTH) values of control and reference-exposed groups were similar, approximately 18 d. In all groups of embryos exposed to natural oil sands (0.1–25.0 g/L), there was significant premature hatching as compared to control embryos (6 d earlier for E-Nat, and 7 d earlier for S-Nat; Figure 3b). Thus, the threshold concentration of natural oil sands producing TTH alterations was below 0.1 g/L, the lowest exposure tested in this study. Exposure to low concentrations of WWP sediments significantly decreased TTH relative to controls (Figure 3b), although not to the same extent as natural oil sands. At low exposures of WWP sediments (0.1–1.5 g/L), embryos hatched significantly earlier (2 d) than controls.

Early Life Stage Toxicity

During hatching, some embryos died partially emerged from the chorion or half hatched. Most sediment-exposure-related mortality occurred posthatch (7–21 dph), and only in those larvae showing malformations. Total cumulative larval mortality demonstrated significant exposure-related increases with natural

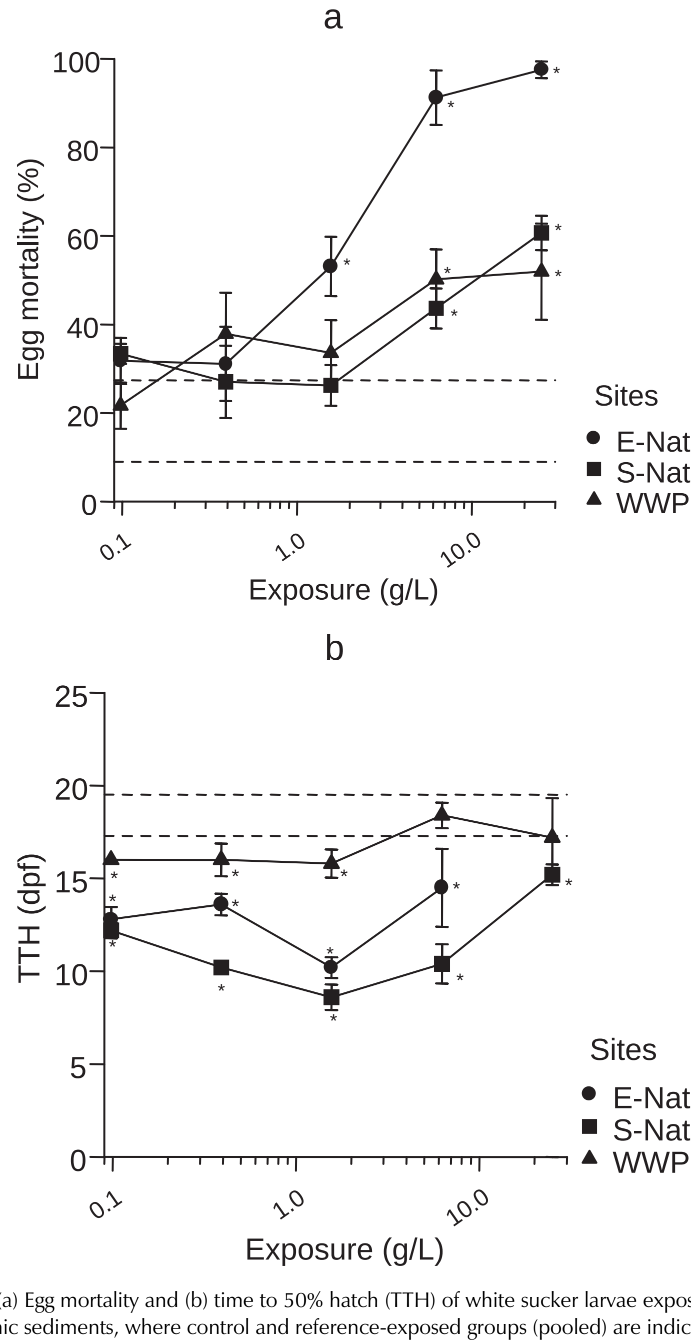

FIGURE 3. (a) Egg mortality and (b) time to 50% hatch (TTH) of white sucker larvae exposed to natural and anthropogenic sediments, where control and reference-exposed groups (pooled) are indicated by 95% confidence limits (– – – –); $n = 5$ replicates/exposure (with 25 eggs/replicate) except E-Nat at 6.25 g/L, where $n = 4$ replicates. The TTH response for E-Nat at 25 g/L was excluded due to low hatching success. Asterisks denote statistically significant difference from pooled controls at $p < .05$.

TABLE 2. Lowest Observed Effect Exposures of Refinery Wastewater Pond (WWP) and Natural Oil Sands (E-Nat and S-Nat) for Producing Various Toxic Endpoints in White Sucker Embryos and Larvae

Endpoints	(g/L)	WWP	E-Nat	S-Nat
Egg mortality (%)	LOEC	6.2	1.5	6.2
Larval mortality (%)	LOEC	1.5 (2028 μg TPAH/L)	0.4 (97 μg TPAH/L)	1.5 (562 μg TPAH/L)
Percent pericardial edema	LOEC	0.4	0.4	0.4
Percent yolk sac edema	LOEC	0.4	0.4	0.4
Percent subepidecimal edema	LOEC	6.2	No effect	No effect
Percent spinal deformity	LOEC	1.5	0.4	1.5
Percent hemorrhages	LOEC	0.4	0.4	0.4
Larval length	LOEC	0.4	0.4	1.5
Larval weight	LOEC	0.1	1.5	0.1
EROD activity	LOEC	0.002	0.115	0.057
	EC50	0.006	2.9	1.8
Time to 50% hatch (TTH)		Premature at low doses (0.1–1.5 g/L)	Premature at all doses	Premature at all doses

oil sands and WWP sediments (Figure 4). WWP- and S-Nat-exposed groups had significantly higher larval mortality at an LOEC of 1.5 g/L, whereas E-Nat-exposed groups had significantly greater mortality above the threshold of 0.4 g/L (Table 2).

There was a very low prevalence of malformations in reference sediment-exposed groups and lab water-exposed controls (<2%). Water controls and reference-exposed groups showed normal pericardial development (~1% had heart edemas) and yolk sacs (edemas absent), straight trunks (~1% had spinal deformities), and minimal hemorrhages (~1% had hemorrhages). From the period of hatch to 21 dph, the majority of WWP-, E-Nat-, and S-Nat-exposed larvae showed signs of BSD. Starting from the highest occurrence, signs included pericardial edema, spinal deformities, hemorrhages, and yolk sac and subepidermal edemas. Generally, the prevalence of malformations (spinal malformations, hemorrhages, pericardial and yolk sac edemas) showed significant exposure-related increases with the E-Nat, S-Nat, and WWP groups (Figure 5). The LOECs for these responses were as low as 0.4 g/L (Table 2). Significant exposure-related increases in subepidermal edemas were demonstrated only in WWP-exposed groups, at and above the threshold of 6.2 g/L (Figure 5). In all exposed groups, hemorrhages reached a maximal value, with higher exposures producing a reduction in the prevalence of hemorrhages (Figure 5). In some high E-Nat-, S-Nat-, and WWP-exposed groups, severely edematous larvae emerged viable, but showed necrotic tissues (trunk, head, heart and/or yolk sac fractions), despite continued heart activity. In most cases, heart and/or yolk sac edemas were responsible for mortality, in that edemas would become so advanced that these tissues would burst, become necrotic, and shortly thereafter these larvae would die. E-Nat-, S-Nat-, and WWP-exposed larvae showed additional malformations in about 10% of individuals.

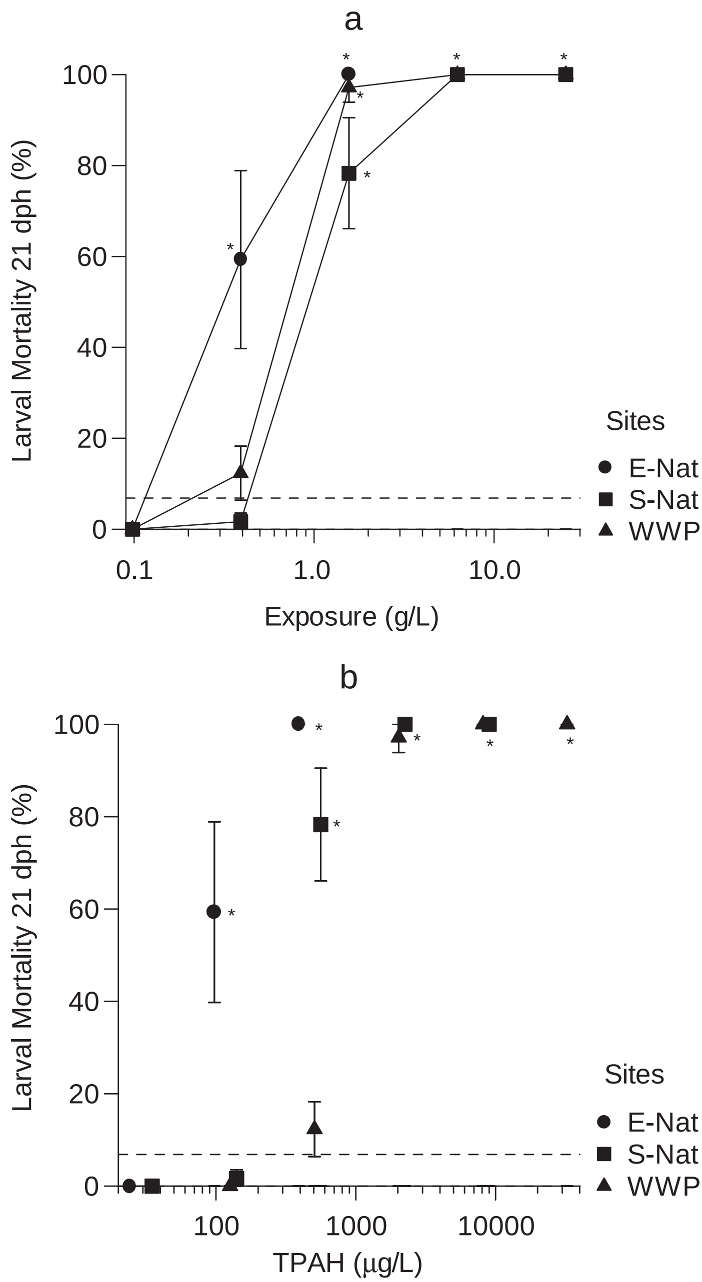

FIGURE 4. Cumulative larval mortality (21 dph) across exposure groups for each site expressed as (a) g sediment/L and (b) estimated TPAH µg/L, where symbols represent means (± standard error), with $n = 5$ replicates per group. Larval mortality for control and reference-exposed groups (pooled) was 5–10% and is represented by the dashed bars. Asterisks denote statistically significant difference from pooled controls at $p < .05$.

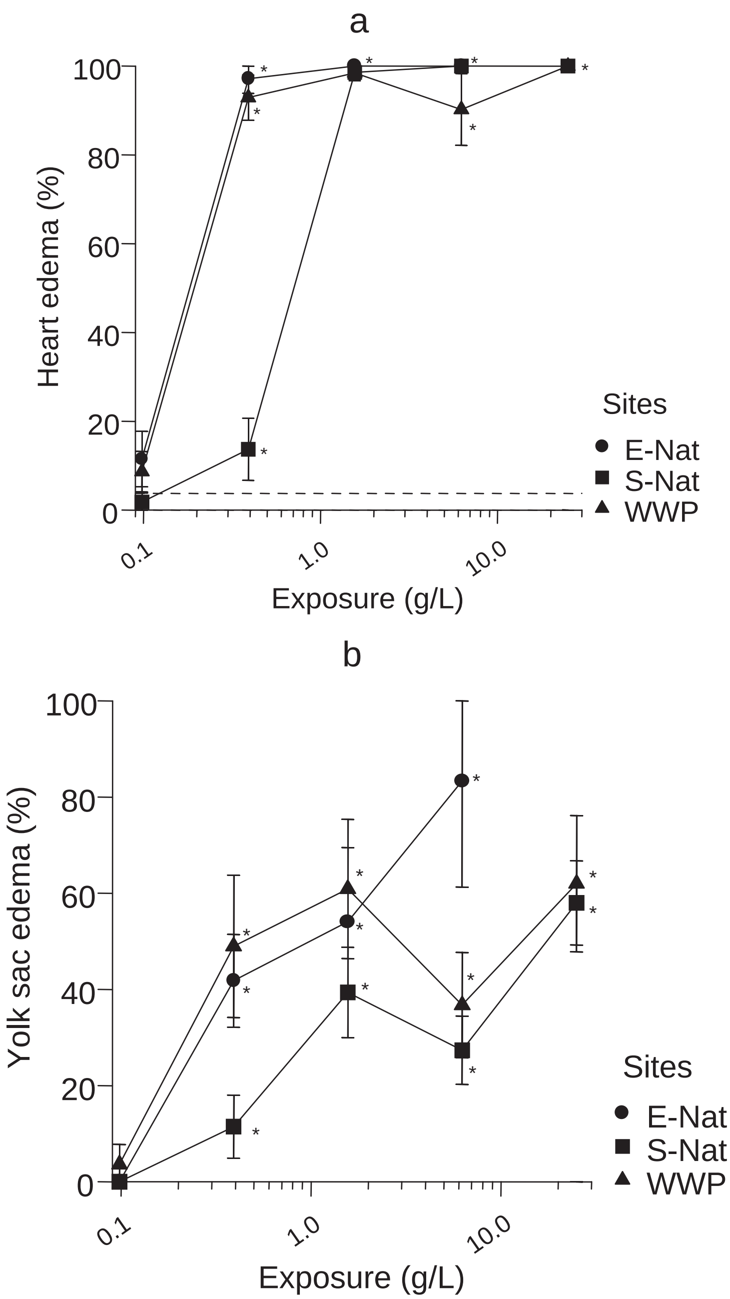

FIGURE 5. Signs of toxicity in white sucker larvae exposed to WWP sediments and natural oil sands. Signs of toxicity include pericardial (heart) edema (a), yolk sac edema (b), subepidermal edema (c), spinal deformities (d), and hemorrhages (e). Asterisks denote statistically significant difference from pooled controls at $p < .05$. Control responses for all variables were ≤1.0%.

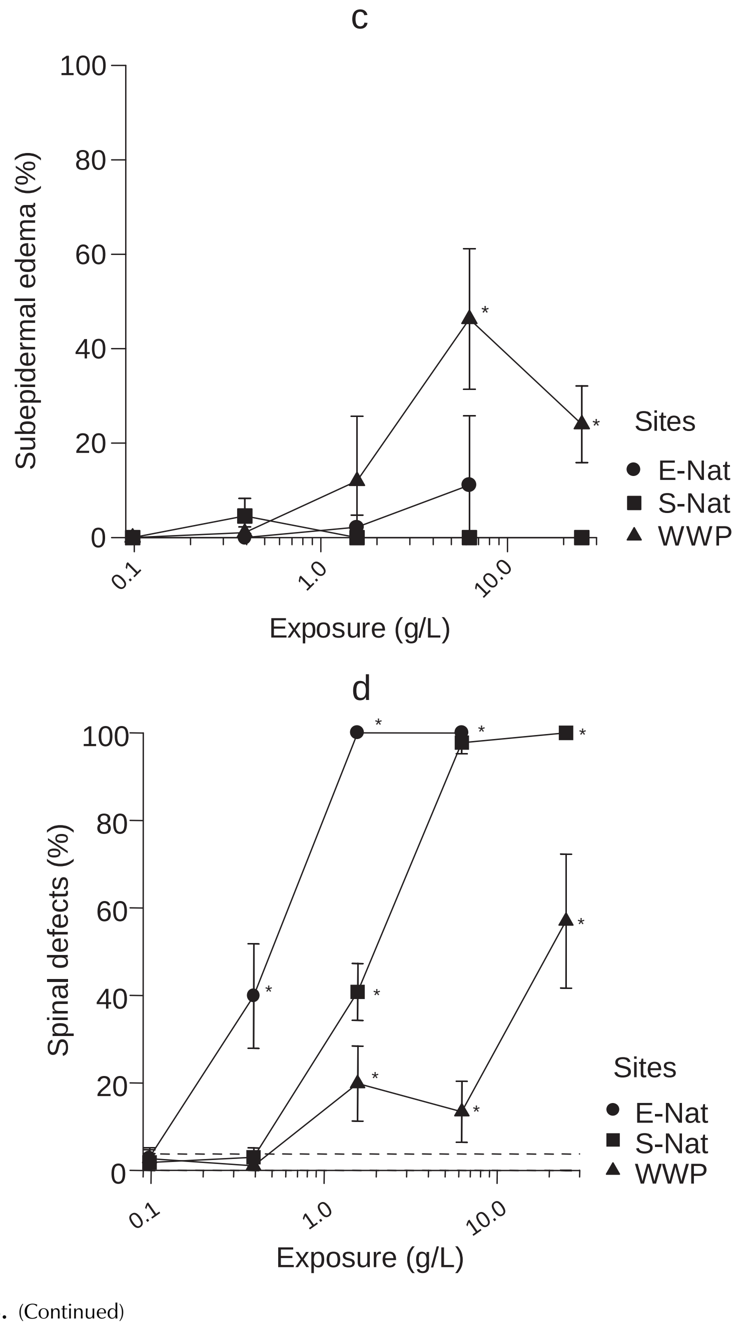

FIGURE 5. (Continued)

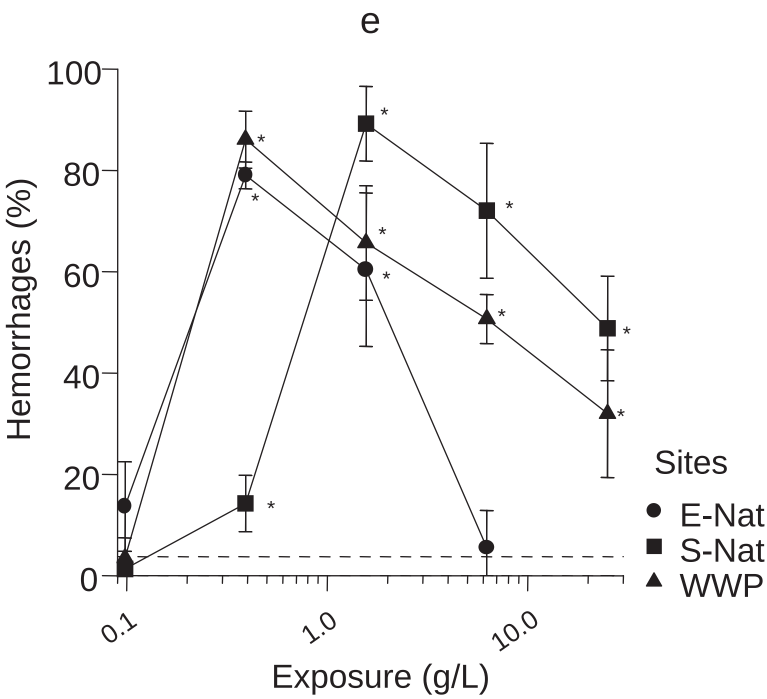

FIGURE 5. (Continued)

These included craniofacial deformities (domed skulls, underdeveloped and protruding jaws), eye alterations, and yolk sac and cardiovascular abnormalities. Alterations in the size or function of the heart were observed but not recorded. Larvae with pericardial edema often had a small-size heart that beat slowly (bradycardia and arrhythmia) and was either empty of blood or filled with static blood. Many larvae in high exposure groups displayed impaired swimming behaviors (twitches, circular swimming) and appeared lethargic at hatch to several days posthatch. None of these abnormalities were observed in control or reference-exposed larvae.

Growth

Hatching size was significantly reduced, as shown by an overall decrease in length with increasing oil sands exposure (Figure 6a). Lengths of larvae in moderate to higher treatments were significantly shorter than control and reference-exposed fish, and threshold effect exposures were estimated to be at or above 1.5 g/L (S-Nat) and 0.4 g/L for both E-Nat- and WWP-exposed groups (Table 2). Growth was significantly reduced, as illustrated by a decrease in weights of E-Nat-exposed larvae in higher treatments relative to controls. Larval weights of all S-Nat- and WWP-exposed groups were significantly reduced as compared to controls (Figure 6b).

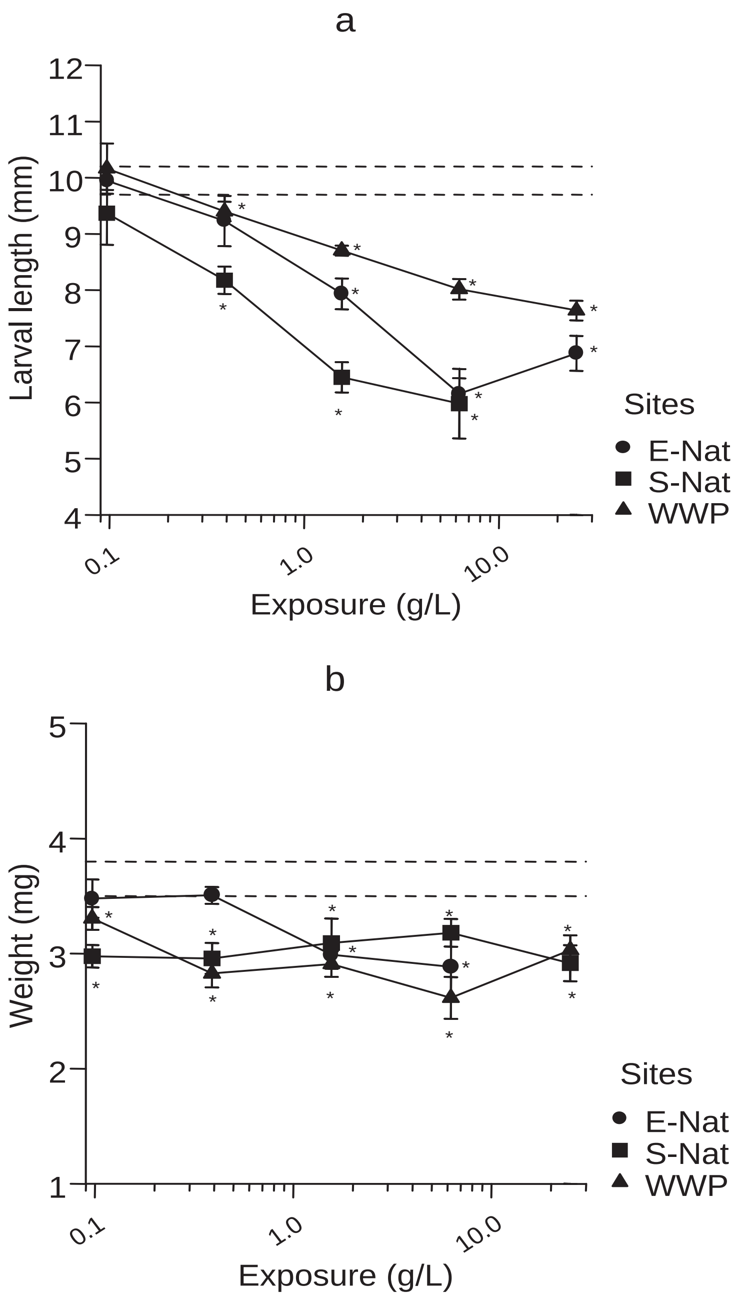

FIGURE 6. (a) Total larval length and (b) wet weight of newly hatched white sucker larvae exposed to natural and anthropogenic sediments; $n = 10$ larvae/group. Asterisks denote statistically significant difference from pooled controls at $p < .05$.

CYP1A Activity

When transferred to aquaria containing sediment, juvenile white suckers generally swam to the bottom, spending most of their time in contact with sediments. Sediment was found in the intestine of several exposed individuals. Although overlaying waters may have been clear at the start of changeovers, the activity of the fish caused sediments to suspend to a minor extent with the overlying water. There was no behavioral evidence of toxicity or distress.

For EROD activity, a well-defined exposure-response relationship was evident with all sediments (Figure 7), with maximum activity of oil sands-exposed juveniles about 30 times higher than that of control fish. Maximum activity of WWP sediment-exposed juveniles was about 50 times higher than that of control fish. In contrast, EROD activity of white suckers exposed to reference sediments was low (1.9 ± 0.8 for E-Ref, and 0.6 ± 0.4 for S-Ref), and similar to water controls (2.2 ± 0.4 pmol/mg/min). BNF-exposed fish showed EROD activity similar to levels observed in fish exposed to E-Nat and S-Nat sediments (41.8 ± 10.2, $n = 5$). Exposure response curves for both natural oil sands were roughly parallel and showed similar values for maximal induction (64.4 to 68.4 pmol/mg/min, S-Nat and E-Nat, respectively). For E-Nat there appeared to be maximum induction at sediment exposures of 7.3 g/L (1800 TPAH μg/L). In contrast, higher maximal EROD induction (114.3 pmol/mg/min) was evident in WWP-exposed fish, and a steeper exposure response curve was produced. In this case, the plateau of EROD induction was at 0.007 g/L (9 TPAH μg/L), with higher exposures producing a lower degree of induction (Figure 7). Threshold effect exposures were estimated to be at and above 0.002, 0.057, and 0.115 g/L for WWP-, S-Nat-, and E-Nat-exposed groups, respectively (Table 2). Based on EC50 values for EROD induction, WWP sediments were about 100 times more potent than natural oil sands. For WWP sediments the EC50 (0.006 g/L) corresponded to a TPAH of 8 μg/L, while EC50s for S-Nat (1.8 g/L) and E-Nat (2.9 g/L) corresponded to TPAH of 650 and 720 μg/L, respectively (Figure 7).

DISCUSSION

Oil Sands Toxicity During Embryo Development

Toxicity from oil sands during embryo development was evident in this study as reduced hatching success with increasing oil sands exposure. Prehatch mortality occurred during organogenesis and just prior to and during hatch. Observations of white sucker embryos dying partially emerged from the chorion were similar to those observed in oil exposures with other fish species such as fathead minnows (Colavecchia et al., 2004), medaka (Rhodes et al., 2005), Pacific herring (Carls et al., 1999; Middaugh et al., 1998), and mummichogs (Couillard, 2002). E-Nat was the most toxic sediment to white sucker embryos, with the highest slope and an LOEC of 1.5 g/L (Figure 3a and Table

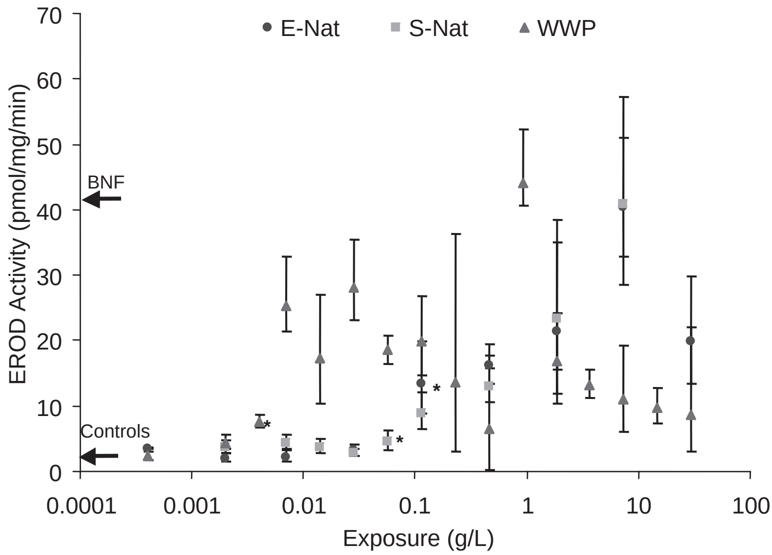

FIGURE 7. The hepatic 7–ethoxyresorufin–*O*-deethylase (EROD) activity in juvenile white sucker exposed to natural oil sands (E-Nat and S-Nat) and anthropogenic WWP sediments. BNF, water and reference-exposed (pooled) responses are indicated by arrows. Asterisks denote statistically significant difference from pooled controls at $p < .05$.

2). E-Nat was also the most toxic sediment to fathead minnow embryos, and there may be a link between PAHs composition and toxicity of different oil sands (Colavecchia et al., 2004). In this study, white sucker embryos showed increased egg mortality rates (10–20% control corrected) as compared to fathead minnow eggs (Colavecchia et al., 2004). Although LOEC values for egg mortality were similar for both species, the elevated egg mortality in white suckers may be associated with their longer incubation period, which ranged from 12 to 18 d, as compared to approximately 4 d for fathead minnows. Furthermore, the gametes obtained for this study were from field-collected adults with unknown genetic, nutritional, and health histories, which may explain the elevated egg mortality in white suckers as compared to laboratory-raised fathead minnows. However, considering the differences among egg characteristics, developmental times, and exposure conditions, measurements of the PAHs levels in the egg tissues would be needed to compare the sensitivities of these two species to oil-sands-induced toxicity.

The present results indicate that ELS exposure to oil sands reduces hatching time, with hatching completed 2–7 d earlier in most exposed groups than in control embryos. Premature hatching was also observed in several fish species exposed to crude oil fractions (Carls et al., 1999; Leung & Bulkley, 1979) and single PAHs (Rhodes et al., 2005). Premature hatching was attributed to the rupture of hatching glands following stimulation of respiration or irritation by soluble hydrocarbons (Leung & Bulkley, 1979). It was hypothesized that this occurred as a consequence of increased metabolic activity, which induced early shivering or embryonic movements, which may enhance mixing of hatching enzymes and thus lead to early emergence. Alterations in TTH were reported by several researchers; however, the effect is not consistent across studies. Some authors reported no differences in TTH (Carls & Rice, 1990), while others reported both premature and delayed hatching, depending on the oil source and dose (Colavecchia et al., 2004; Linden, 1978). It appears that there are factors that have not yet been identified that can alter hatching in the presence of toxic chemicals.

Oil Sands Toxicity After Hatch

ELS exposure of white suckers to oil sands produced mortality as well as a number of sublethal effects, including larval malformations and reduced size. Deformities included exposure-related increases in the prevalence of spinal defects, edemas (pericardial, yolk sac, and subepidermal), and hemorrhages. Most of these adverse responses have been reported following embryonic oil exposure in a variety of fish species (Carls et al., 1999; Carls & Rice, 1990; Couillard, 2002; Linden, 1978; Marty et al., 1997a, 1997b). Observed malformations appear sufficient to decrease larval survival, with larval mortality thresholds for natural oil sands and WWP sediments between 0.4 g/L (NOEC) and 1.5 g/L (LOEC). Similar to embryos, larvae showed that E-Nat was the most toxic sediment, with larval mortality thresholds between 0.1 and 0.4 g/L (NOEC and LOEC). The PAHs composition of E-Nat sands differs from other sites, containing relatively larger quantities of phenanthrene/anthracene (>60%) and its alkylated derivatives (Figure 2).

Of the observed deformities, pericardial edema appeared to be responsible for most of the larval mortality. Larval malformation thresholds (hemorrhages, pericardial and yolk sac edemas) for all sites were similar, between 0.1 (NOEC) and 0.4 g/L (LOEC). Colavecchia et al. (2004) reported that pericardial edema in oil sands-exposed fathead minnows was the most sensitive morphological response, and may be linked to cardiac insufficiency and ELS mortality. In both field and lab experiments exposing Pacific herring (*Clupea pallasi*) eggs to crude oil, ascites (the histological equivalent of edema) was the most significant lesion related to oil exposure (Marty et al., 1997b). Middaugh et al. (2002) reported that cardiovascular malformations in oil-exposed inland silversides (*Menidia beryllina*) were associated with reduced cardiac output and cessation of circulation. It was hypothesized that pericardial edema may restrict blood flow to developing tissues, resulting in decreased growth, degeneration of tissues, and death in exposed larvae (Colavecchia et al., 2004; Marty et al., 1997b).

Although edema pathogenesis was not evaluated in this study, blood flow restrictions are evident as increased prevalence of hemorrhages at lower oil sands exposures (Figure 5e). Subcutaneous hemorrhage is a common response in embryonic exposure to PAHs (Winkler et al., 1983) and is considered to be one of the earliest signs of cardiovascular dysfunction (Brinkworth et al., 2003;

Henry et al., 1997). In mild cases, exposed larvae showed edema and hemorrhages. In more severe cases, there was increased fluid within the pericardial cavity, reduced and irregular heartbeats, and no blood in the heart. In these severely edematous larvae, yolk sacs and hearts were sometimes observed as ruptured and necrotic. Several studies reported pericardial edema, bradycardia, and arrhythmias in fish embryos exposed to oil fractions (Linden, 1978; Middaugh et al., 2002). Further signs of possible vascular dysfunction may be related to the observed necrotic tissues of exposed larvae. Ruptures of the yolk sac and pericardial cavity were also reported for several larval fish exposed to single PAHs (Brinkworth et al., 2003) and crude oil fractions (Marty et al., 1997b). In the latter study, significant degenerative and necrotic lesions of skeletal myocytes, retinal cells, and brain cells were related to oil exposure. It was suggested that in severe cases of pericardial edema, blood flow is sufficiently restricted that tissues burst, become necrotic, and fish die. More detailed studies quantifying heart rates and blood flow would be useful in determining the effects of oil sands induced toxicity on cardiac output.

Exposure-related increases in subepidermal edemas were seen only in WWP-exposed larvae. These edemas resembled membranous vesicles found in pollock (*Theragra chalcogramma*) embryos exposed to 2.4 ppm of water-soluble crude oil fractions (Carls & Rice, 1990). The frequency, quantity, and size of vesicles correlated positively with oil concentrations; however, polyaromatics were not measured. Carls and Rice (1990) suggested that vesicle formation may be produced by ionic disturbances as a result of aromatic hydrocarbons altering cell membrane permeability. WWP sediments contain the highest TPAH concentration (1300 μg/g), with high-molecular-weight (HMW, 4- to 6-ring aromatics) compounds in greatest abundance (>90%), particularly benz[a]anthracene/chrysene (BAC 56%) and benzofluoranthene/pyrene (BFLPY 28%; Figure 2). Since WWP sediments are settled solids from oil sands refining operations, there are additional OSRCs that were not evaluated, which may contribute to toxicity. Naphthenic acids (NAs) are a family of carboxylic acids that are abundant in oil sands wastes and are acutely toxic to aquatic organisms (Alberta Department of Energy, 1995). In addition, C_{1-4} dibenzothiophenes (DBT) are sulpfur-containing compounds that are typically found at high concentrations in natural oil sands and tailings extracts (Headley et al., 2001; Rhodes et al., 2005). Rhodes et al. (2005) suggested that the high proportion of C_2-substituted DBT in oil sands extracts may be contributing to the increased toxicity observed in exposed medaka. The toxicity of weathered crude oils to marine organisms has also been correlated with polar, low-molecular-weight (LMW) hydrocarbon degradation products (Middaugh et al., 2002). Due to the complexity of WWP sediments, toxicity identification evaluation studies are needed to determine causative agents.

Exposure-related increases in spinal malformations were seen, with thresholds between 0.4 (NOEC) and 1.5 g/L (LOEC). E-Nat was the most potent sediment producing spinal defects, with a threshold response between 0.1 and 0.4 g/L (NOEC and LOEC). Pacific herring exposed to crude oil showed significant exposure-related increases in spinal curvatures and reduced swimming ability (Carls et al., 1999). Further, larval size at hatch decreased with increasing oil sands exposure. Retarded larval growth was reported in several fish species exposed to alkyl–phenanthrene (Billiard et al., 1999), crude oil fractions (Carls et al., 1999; Carls & Rice, 1990; Linden, 1978; Marty et al., 1997b), oil sands wastewaters (Siwik et al., 2000), and natural oil sands (Colavecchia et al., 2004). It was suggested that energy for somatic growth is decreased by increased energy demands related to hydrocarbon metabolism and excretion. Pink salmon (*Oncorhynchus gorbuscha*) larvae from oiled areas, which had higher prevalence of ascites, also grew less and had significantly less food within their gastrointestinal tracts than larvae from unoiled areas (Marty et al., 1997b). Oil-exposed Pacific herring eggs hatched earlier than unexposed larvae, and larvae were smaller and more immature, as indicated by shorter body lengths, larger yolks, smaller jaws, and immature fins (Carls et al., 1999). In field mesocosms, native fathead minnows reared in oil sands tailings showed reduced growth compared to fish in nonprocessed waters (Siwik et al., 2000). Retarded growth and spinal malformations may be a consequence of reduced blood flow (Billiard et al., 1999). For a better understanding of the possible relationship between these malformations, it would be useful to look at the temporal succession and the severity of the observed abnormalities. The similarity of exposure-response curves for the various malformations indicates that the mechanism of toxic action among oil sands sites was similar.

Comparative Toxicity and Mechanisms

The symptoms of oil sands toxicity in white suckers are consistent with those observed in several other fish species exposed to a variety of toxic substances that bind with the aryl hydrocarbon receptor (AhR), including dibenzo-*p*-dioxins (Henry et al., 1997; Elonen et al., 1998), alkyl phenanthrenes (Billiard et al., 1999; Brinkworth et al., 2003), and PAHs in crude oil (Carls et al., 1999; Couillard, 2002; Marty et al., 1997a, 1997b) and natural oil sands (Colavecchia et al., 2004). Dioxin-induced blue sac disease (BSD) is a syndrome characterized by increased ELS mortality and malformations (edema, hemorrhages, and spinal defects) and has been associated with CYP1A induction in endothelial tissues of exposed fish. The similarity of toxic effects of oil sands and related aromatic compounds in different fish species indicates that the AhR-mediated mechanism may be responsible for toxicity in these organisms. The mechanism of action underlying the toxicity of AhR-binding chemicals is only partially understood, but is believed to involve CYP1A induction, oxidative stress, and endothelial cell damage (Cantrell et al., 1998). Regardless of the specific mechanism responsible for the toxicity observed in each fish species, differences in sensitivity may be related to species sensitivity differences in ELS development patterns, dose to vulnerable tissues, and physiology.

The consistency of responses in two species, white sucker and fathead minnow (Colavecchia et al., 2004), suggests that these results may be generally applicable to other fish species. Despite differences in egg size, habitats, development times, and conditions, LOECs for sublethal responses to oil sands were similar between these two species. In contrast, LOECs for larval mortality were lower in fathead minnow larvae (0.05–0.8 g/L) than in white sucker larvae (0.4–1.5 g/L), indicating greater sensitivity to oil sands exposure. The relative sensitivity of fathead minnow embryos to 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) compared to other fish species may reflect their sensitivity to petroleum PAHs. Fathead minnow eggs exposed to TCDD are more sensitive (LC50egg = 22,500 pg TCDD/g lipid) than white sucker eggs (LC50egg = 75,600 pg/g lipid) and zebrafish embryos (LC50egg = 153,500 pg/g lipid; Elonen et al., 1998). A comparison of the exposure-response curves showed that the relationship between larval mortality and sediment-TPAH was similar for both species, which is consistent with the hypothesis that the mode of toxic action of oil sands is probably the same for these two species. Limited data exist for species differences in toxicokinetics and toxicodynamics that may contribute to the sensitivity differences observed following ELS exposures to oil sands.

Ethoxyresorufin–*O*-Deethylase (EROD) Activities in Juveniles

The bioavailability of sediment OSRCs was investigated by measuring EROD activity in reference fish exposed to natural oil sands and industrially contaminated WWP sediments. The consistent exposure-related increases in hepatic detoxifying enzymes among the sites demonstrate that fish were exposed to OSRCs from these sediments and that an increase in metabolic effort occurred as a result of exposure.

Numerous studies demonstrated the induction of CYPIA activity in fish following laboratory (Basu et al., 2001; Billiard et al., 1999; Marty et al., 1997b; Oikari et al., 2002; van der Weiden et al., 1994) and field exposure (Spies et al., 1996; Stagg et al., 1995; VanVeld et al., 1990) to petroleum hydrocarbons and PAHs. Altered CYP1A induction has been demonstrated in wild fish collected from sites impacted by oil spills (Stagg et al., 2000; Woodin et al., 1997). Chemical analyses of sediments from this region show high concentrations of alkyl-substituted PAHs, typical of petroleum-source PAHs (Colavecchia et al., 2004; Headley et al., 2001). The main chemical compounds in SPMDs from surface waters in the Athabasca oil sands region were aromatic and alkyl-PAHs, NAs, benzothiophenes, and methyl carbazoles (Parrott et al., 1996). Exposure of a fish cell line to these extracts demonstrated significant induction of EROD activity, indicating the presence of naturally occurring MFO-inducing compounds (Parrrott et al., 1996). Extracts of SPMDs deployed within the oil sands area on the Ells and Steepbank Rivers also elevated cell line MFO activity (Parrott et al., 2002). In contrast, SPMD extracts from upstream reference sites showed little or no induction of MFO activity. A field study of native fish species from this region showed significant increases in EROD activity with distance downstream of reference sites; EROD activity was low in reference fish, increased in fish from natural oil sand sites, and was highest in fish collected at developed sites (Tetreault et al., 2003a). In a related lab exposure, slimy sculpin (*Cottus cognatus*) demonstrated a significant graded response in EROD induction, comparable to that observed in wild resident fish (Tetreault et al., 2003b). Based on EC50s, the CYP1A-inducing potencies of the sites in our study are highest in WWP-exposed fish >> high in natural oil sands-exposed groups (E-Nat and S-Nat) >> low/negligible EROD activity in reference groups (E-Ref and S-Ref). Maximal induction values and the graded EROD response observed in white sucker from this study confirm earlier wild fish assessments and SPMD results from this region. In addition, CYP1A induction levels reported here are similar in magnitude to values reported for fish collected from a natural petroleum seep (Spies et al., 1996) and sites contaminated by oil spills (Woodin et al., 1997).

The WWP in this study contains cooling waters, runoff, and settled solids from Suncor Energy, and is directly impacted by oil processing operations. Increased MFO activity and bile PAHs metabolites in yellow perch exposed to tailings wastewaters relative to reference fish suggest this to be a response to OSRCs at this site (van den Heuvel et al., 1999). In this study, exposure dependency was lost at high WWP sediment exposures, suggesting limits on desorption kinetics, or saturation of accumulation rates, or accumulation of toxic concentrations that would impair the EROD response (Hodson et al., 1996). Similar EROD induction dose-response curves have been described for PAHs mixtures (Fent & Batscher, 2000; Oikari et al., 2002). Furthermore, WWP sediments may contain more EROD-inducing compounds than natural or reference sediments. In this study, the differences in CYP1A inducing potencies among sites were closely associated with sediment TPAH concentrations. The relatively low EROD activity in reference-exposed groups was consistent with the low sediment TPAH levels from those sites (0.03–2.4 μg/g), while natural oil sands with higher TPAH concentrations (250–360 μg/g) had higher EROD activity, and WWP sediments with the highest sediment TPAH concentrations (1300 μg/g) had the lowest EC50 for EROD induction. In addition, WWP sediments differ in physiochemical composition from natural oil sands and reference sediments (Colavecchia et al., 2004), and may contain highly potent inducers of EROD activity. HMW PAHs (4 to 6 ring PAHs) are abundant in WWP sediments (>92% of TPAH) and include benz[a]anthracene/chrysene (BAC), benzofluoranthene/pyrene (BFLPY), and fluoranthene/pyrene (FLPY, Figure 2). HMW PAHs were suggested to be among the most potent MFO-inducing compounds in petroleum (Basu et al., 2001; Woodin et al., 1997; Stagg et al., 1995, 2000). Natural oil sands contained higher levels of LMW PAHs (29–66% of TPAH: S-Nat and E-Nat), particularly C_{1-4} phenanthrene/anthracene (P1–4), which may also be important inducing compounds in these sediments. Additional unknown inducing compounds, including unidentified PAHs and alkyl-PAHs, nitrated PAHs, dibenzothiophenes, NAs, or hydrocarbon degradation products, may be present. Due to the chemical complexity of these sediments, more detailed studies are necessary to identify the compounds associated with EROD induction by oil sands. This short-term lab bioassay can be used in conjunction with a toxicity identification evaluation

(TIE) in order to identify MFO-inducing and BSD-producing compounds in Athabasca oil sands sediments.

CONCLUSION

Exposure to oil sands sediments impairs the development and survival of white sucker eggs and larvae. Oil sands-exposed eggs hatched early, and showed significant exposure-related increases in ELS mortality, malformations, and retarded larval growth relative to control and reference-exposed groups. Although the ecological implications of the toxic actions of oil sands exposure remain unassessed, reduced hatching success could adversely affect reproductive success in fish populations. Two important biological consequences of the observed sublethal effects may be impaired swimming and feeding ability. Therefore, smaller and malformed larvae are more susceptible to predation, starvation, and mortality. The direct application of the results of lab bioassays to field conditions can be problematic. Season, diet, general health, and interspecies differences in metabolism, excretion, and behavior are just a few factors that could influence the response of native fish species to oil sands exposure. The presence of other contaminants (NAs, DBT, hydrocarbon degradation products, metals) and their potential interactions, along with natural variability of physiochemical factors (natural water flows, volatilization, evaporation, and ultraviolet radiation), would be expected to modify the bioavailability and toxicity of PAHs in oil sands.

Experiments that extend exposure periods from the egg, past juvenile stages through to the spawning adult stage, would help determine the nature and extent to which oil sands may elicit additional development or reproductive effects in fish. Native short-lived, early-maturing species could be used for *in situ* studies to evaluate the effects of oil sands on reproductive success, with emphasis on ELS survival, developmental abnormalities, sexual development, mating behavior, and fecundity using corresponding biochemical (EROD induction, bile PAHs) and histological biomarkers.

Exposure-related increases in EROD induction show bioavailability of OSRCs from both natural and anthropogenic oil sands materials, at exposures greater than 2 mg/L (2.6 TPAH μg/L). Maximal induction values and the graded EROD response observed in this study are comparable to earlier results from this region. This short-term lab bioassay can be a useful test for monitoring physiological responses to PAHs and petroleum. Additional related lab studies, such as depuration experiments, length of exposure, and time course of EROD induction, would be useful in better understanding the kinetics of EROD induction in relation to oil sands exposure. This study emphasizes the need for conducting studies using real mixtures of environmental contaminants, such as whole sediments, when an understanding of the effects of petroleum contamination is desired.

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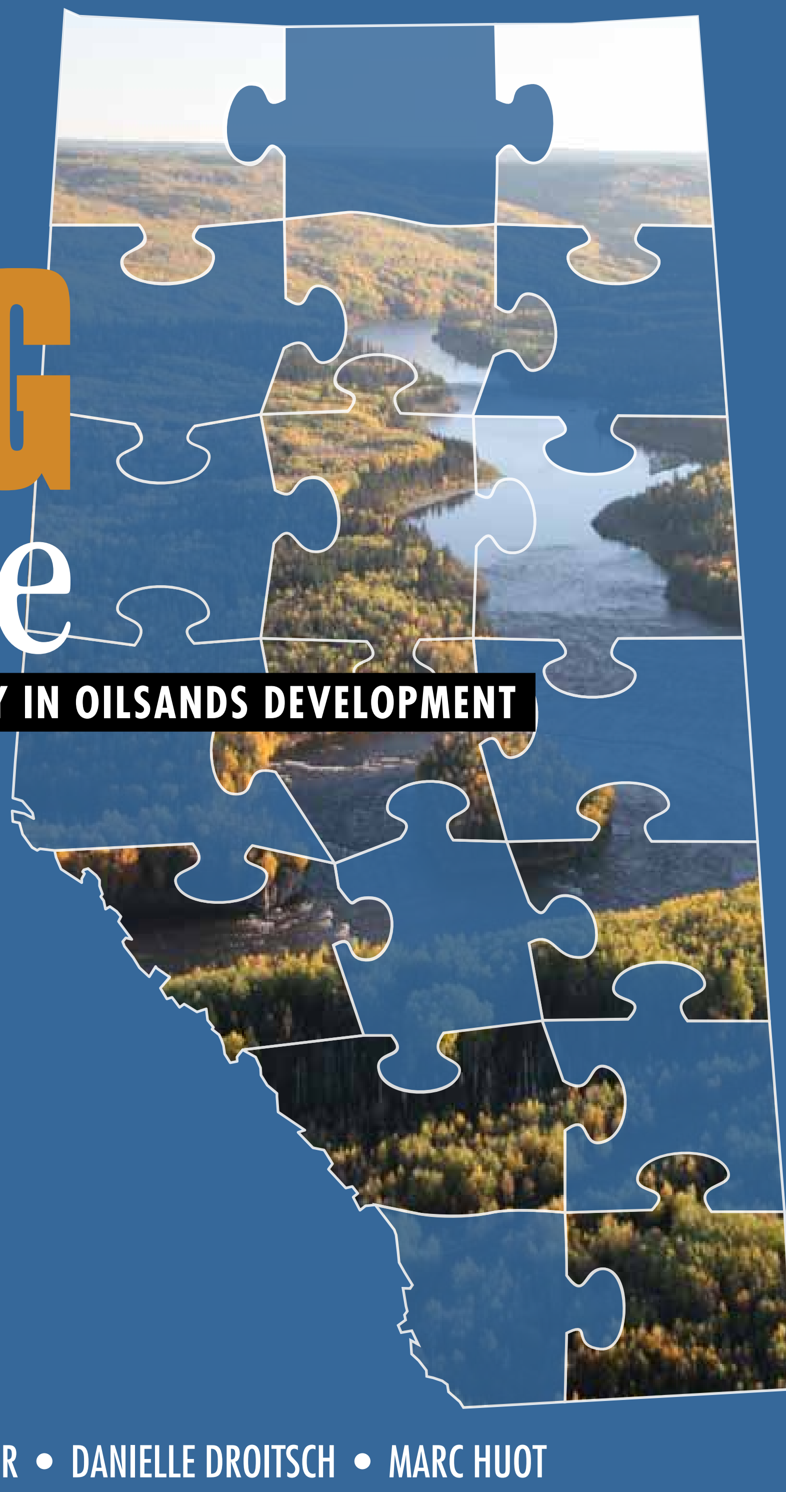
SOLVING the Puzzle



ENVIRONMENTAL RESPONSIBILITY IN OILSANDS DEVELOPMENT

JENNIFER GRANT • SIMON DYER • DANIELLE DROITSCH • MARC HUOT

APRIL 2011

the PEMBINA institute

Oil SANDS Fever SERIES

Solving the Puzzle

Environmental responsibility in oilsands development

Jennifer Grant • Simon Dyer • Danielle Droitsch • Marc Huot

April 2011

SOLVING the Puzzle

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The Pembina Institute
Box 7558
Drayton Valley, Alberta
Canada T7A 1S7
Phone: 780-542-6272
Email: info@pembina.org

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About the Authors

Jennifer Grant

Jennifer Grant is the director of the Pembina Institute's oilsands program. She has worked with the Institute since 2006 on the environmental impacts of Canadian oilsands development and cumulative effects and land use planning in the North. Jennifer represented the Pembina Institute on the Reclamation Working Group and the Watershed Integrity Task Group of the Cumulative Environmental Management Association. Jennifer holds a Master of Science in ecosystem management from the University of Calgary and a Bachelor of Science in biological sciences from the University of Victoria.

Simon Dyer

Simon is policy director at the Pembina Institute, and former director of the Institute's oilsands program. A professional biologist, Simon has worked on natural resource management issues in western Canada since 1999. Simon holds a Master of Science in environmental biology and ecology from the University of Alberta, and a Master of Arts in natural sciences from the University of Cambridge. Simon is the co-author of over 20 Pembina Institute publications and has represented the Institute at many regulatory and parliamentary hearings and multistakeholder processes.

Marc Huot

Marc is a policy analyst with the Pembina Institute's oilsands program. Marc is involved with researching and reviewing environmental impacts associated with oilsands development. His technical background includes knowledge of renewable energy, life cycle assessment methodology, and energy systems. Marc holds a Bachelor of Science and a Master of Science in mechanical engineering from the University of Alberta.

Danielle Droitsch

Danielle is director of U.S. policy at the Pembina Institute. She joined the Institute in 2010 working in Washington D.C. Previously, she held positions as the Executive Director of WaterMatters, an Alberta-based organization focused on watershed protection, and as director of Bow Riverkeeper, part of the Waterkeeper Alliance. She has worked for U.S.-based organizations on energy, national parks and watershed protection. Danielle has authored a number of publications on a range of law and policy issues under both Canadian and United States environmental laws. She has a degree in law from the University of Tennessee and undergraduate degrees in science and history from James Madison University.

Contents

List of Figures

List of Tables

Executive summary

The Government of Alberta faces a narrow and critically important window of opportunity to raise the bar on oilsands development. While there are new plans and frameworks in development that strive to "use a cumulative effects management approach to balance economic development opportunities and social and environmental considerations,"[1] we question if the emphasis placed on these considerations is capable of achieving the environmental outcomes consistent with the expectations of Albertans and Canadians. It is time to set higher standards and improve the rules governing oilsands development.

In *Solving the Puzzle: Environmental responsibility in oilsands development,* the Pembina Institute presents a 19-point plan that identifies policies required to protect the environment and restore Alberta's international reputation.

pol·i·cy

noun, often attributive

a definite course or method of action selected from among alternatives and in light of given conditions to guide and determine present and future decisions[2]

The Athabasca River in winter.

PHOTO: JENNIFER GRANT, THE PEMBINA INSTITUTE

LAND

- ❑ The Alberta Government should legislatively protect at least 50% of its public forest lands from industrial development. Protected areas should be developed and co-managed with Aboriginal peoples.
- ❑ Require establishment of biodiversity offsets for all oilsands development to offset impacts to all habitat types. To ensure a net positive environmental benefit and address existing cumulative effects, offsets should be established with a 3:1 offset ratio — three hectares of land should be conserved or restored for every hectare of new disturbance that occurs within the Boreal Forest Natural Region.
- ❑ Land use plans should mandate that no more than 5% of any Alberta planning region is available to oilsands development at any time.
- ❑ Develop a new, transparent and risk-averse mine security program that ensures the Alberta government collects financial security equivalent to the total liabilities created by oilsands extraction.
- ❑ Follow the recommendations of the Alberta Caribou Committee and demonstrate that all caribou ranges in Alberta meet science-based objectives to maintain caribou populations through a combination of establishing protected areas, setting thresholds on maximum levels of development in caribou habitat, and establishing biodiversity offsets in caribou habitat.

WATER

- ❑ Alberta Environment should complete a water management plan that identifies a science-based Ecosystem Base Flow (EBF) for the lower Athabasca River, as a low-flow threshold below which all water withdrawals would cease. The EBF should be legally enforceable and all water permits issued by the Alberta Government at any one time should be accountable to meet that EBF. In the interim, the low-flow threshold for the lower Athabasca River should be at least 100 m^3/s.
- ❑ Measure and map the quantity and quality of groundwater and surface/groundwater interactions, to determine both the short and long-term sustainable yield of non-saline groundwater in the Lower Athabasca's groundwater management areas. Set legal requirements to implement and enforce the sustainable yield of groundwater.
- ❑ Ensure enforceable regulations are in place to protect non-saline groundwater resources by updating and implementing existing guidelines and definitions. To protect more of our finite water resources, the Alberta government should expand its definition of regulated groundwater from the current level of water containing less than 4,000 mg/l of total dissolved solids (or TDS, a measurement of mineral, salt and metal content) to include water with up to 10,000 mg/l TDS.
- ❑ New mines should not be approved until the operation adopts a proven technology that eliminates the creation of wet tailings. In the interim, all current mines must be required to conform to the new tailings rules.

- ❑ Mine applications that propose the storage of tailings under end pit lakes as their reclamation strategy should not be approved. Existing operations with approved end pit lake plans should be modified to eliminate the need for end pit lakes as long-term storage sites for toxic tailings waste.

AIR

- ❑ Establish air emission limits to achieve the World Health Organization's Air Quality Guidelines to protect air quality and human health. Implement a progressive, multi-tiered system that requires varying degrees of action to prevent degradation of ambient air.
- ❑ Require oilsands operations to use equipment with the lowest achievable emissions or to deploy best-available technology for air emissions reductions.

GREENHOUSE GASES

- ❑ Commit to an Alberta greenhouse gas emissions reduction target consistent with a fair Alberta contribution to prevent dangerous levels of global warming (defined as keeping the global average temperature increase to 2°C, relative to the pre-industrial level).
- ❑ Implement a carbon dioxide equivalent (CO_2e) emissions price, as either a full auction cap-and-trade system or a carbon tax covering all combustion and almost all fixed process emissions (i.e., covering the vast majority of Alberta's emissions).
- ❑ Mandate the use of capture and storage (CCS) technology to capture greenhouse gas emissions from all major new industrial sources by 2016, This would apply to: all formation carbon dioxide (CO_2) from new natural gas processors; all process CO_2 from new hydrogen production facilities; and all combustion CO_2 from all new coal fired electricity plants, oilsands facilities, and upgraders.

MONITORING

- ❑ Ensure full funding of the Alberta Biodiversity Monitoring Institute, either directly from government or through an equitable funding model that requires all natural resource developers who impact biodiversity to contribute as a mandatory component of the regulatory approval process.
- ❑ Expand air monitoring to meet scientific needs. Monitoring design should be developed through a consensus-based approach with full stakeholder input, and with government implementing final decisions.
- ❑ Disband the Regional Aquatics Monitoring Program and replace it with a comprehensive, scientifically robust monitoring system that is adequately resourced and free of industry influence.
- ❑ Make a long-term commitment to fund a regional monitoring network to monitor and assess trends in groundwater levels and groundwater quality indicators.

Introduction

> "The current visibility of relevant provincial and federal agencies, in particular in dealing with the major environmental challenges is low, and is generally not in line with those challenges."
>
> ---The Royal Society of Canada Expert Panel[3]

Global criticism of oilsands development shows no sign of abating. Nor should it, so long as the scale and scope of oilsands impacts outstrip the governments' willingness and ability to act as a responsible steward. Plans to double production within the decade will only intensify regional impacts, and further expose the gap between the rhetoric and reality of cumulative effects management in northeastern Alberta.

Despite beginning to talk about the need to address cumulative impacts, Alberta's delivery of new policy has been unable to keep pace with the scope and scale of development. Through the Land-use Framework process, the Government of Alberta has for the first time committed to setting cumulative environmental limits to inform oilsands development, through the Lower Athabasca Integrated Regional Plan. In April 2011, the province released its final draft of this plan for a 60-day consultation period.

While the draft Lower Athabasca Integrated Regional Plan (LAIRP) acknowledges that a cumulative effects management approach is required and that objectives must be set for environmental, social and economic outcomes, the plan also included many gaps; there is no plan to protect threatened woodland caribou and still no regional disturbance limit. The Pembina Institute argues that the environmental objectives being sought in the draft LAIRP are compromised by commitments made to developers prior to the proposal of the LAIRP, in effect allowing past decisions that favoured accelerated development to undermine the ability of the regulator to protect the public interest.[4]

In *Solving the Puzzle*, Pembina offers concrete suggestions on where the LAIRP could go further in achieving the environmental outcomes expected by Albertans, Canadians and increasingly, the international community.

The Pembina Institute has focused on solutions to address the need for responsible oilsands development for many years. In 2007 Pembina released *Oilsands Fever: Blueprint for Responsible Oilsands Development*,[5] which outlined six essential elements for responsible oilsands development:

1. **Limit environmental impacts:** Apply science-based precautionary limits that tell us when ecosystems are threatened, so that we can make informed decisions about whether and how oilsands projects proceed.
2. **Address cumulative impacts:** Improve the systems and approaches for monitoring and addressing the impacts of

oilsands development on the climate, air, fresh water, boreal forest and wildlife.

3. **Focus on quality of life:** Manage the rate of oilsands growth to maximize the benefits to Albertans' quality of life, and ensure that social services and infrastructure can keep pace.
4. **Think like an owner:** Reform the oilsands royalty regime so that Albertans obtain maximum value from the development of the resources they own.
5. **Make better decisions for Albertans:** Reform the Energy and Utilities Board's[6] decision-making process so that the public interest comes first and only responsible oilsands projects proceed.
6. **Plan for the future:** Take advantage of Alberta's prosperity so as to build a more diversified, green and competitive future that includes low-impact renewable energies and responsible energy use.

These six elements offer a useful yardstick against which to assess any policy framework for management of the oilsands resource, but in Pembina's opinion, little progress in addressing these themes has been made. As well, although this was not specifically addressed in Blueprint, Pembina recognizes the imperative of ensuring that future oilsands development meets the needs of Aboriginals living in project-affected communities, and maintains that project approval be conditioned on the demonstration of free, prior and informed consent. Additional information on Aboriginal communities' concerns about the impacts of oilsands development and their legal rights is reported elsewhere.[7]

In 2010, the Pembina Institute released *Duty Calls*, a report that outlined the role of the federal government in achieving responsible oilsands development.[8] In *Solving the Puzzle*, Pembina goes further, offering 19 critical actions that the Government of Alberta could take to help

limit environmental impacts and address cumulative effects. This report outlines appropriate environmental limits and performance standards for oilsands development, from the perspective of both scientific and public interest, that should be considered in combination to ensure the cumulative impacts of oilsands development are meaningfully addressed.

The opportunity to responsibly develop the oilsands is clearly available to Albertans. Government, industry and the citizens of Alberta can set appropriate regional limits that protect the environment, achieve higher levels of performance from oilsands operations, and deliver on the economic opportunity represented by the resource. Further, the magnitude of economic opportunity, perhaps unprecedented in Canadian history, can help Alberta to be a leader in the global transition to a low carbon and low-impact clean energy future.

The Pembina Institute will report on Alberta's progress toward achieving responsible oilsands development at www.pembina.org/oil-sands/solutions.

Cumulative impacts of oilsands development on the environment must be meaningfully addressed.

PHOTO: DAVID DODGE, CPAWS

Land

Establish 50% protected areas

Ensuring Alberta develops an adequate network of protected conservation lands is an important element of responsible oilsands management. It is not surprising that oilsands mines and intensive in situ developments have impacts on wildlife and forests, but a significant failure to address regional conservation issues has contributed to criticism of oilsands mismanagement.

Protecting wildlife and forests involves more than reclamation, although unfortunately this is often the only land-related issue that comes up under discussions of oilsands impacts on ecosystems.

One solution for land protection is to ensure that enough land area in the regions is kept intact to maintain habitat for the wildlife that Albertans value. This can be achieved through establishing a world-class network of protected areas free of industrial activity. Unfortunately, Alberta's existing protected areas network is not adequate to meet these outcomes. Currently only 12.5% of Alberta is protected from industrial activity,[9] while in the Lower Athabasca Region, where oilsands development is currently focused, only 6.7% of the land area is protected.[10]

Alberta and Canada are far from leaders in conserving an adequate percentage of their land base from industrial development. Many countries have established far higher percentages of their terrestrial ecosystems as legislatively protected areas (see Figure 1). Alberta with its low population, significant amount of intact habitat and large projected impacts associated with oilsands development could be a world leader in land conservation.

There is no clear threshold for the appropriate level of protected areas, although higher levels of protection will conserve

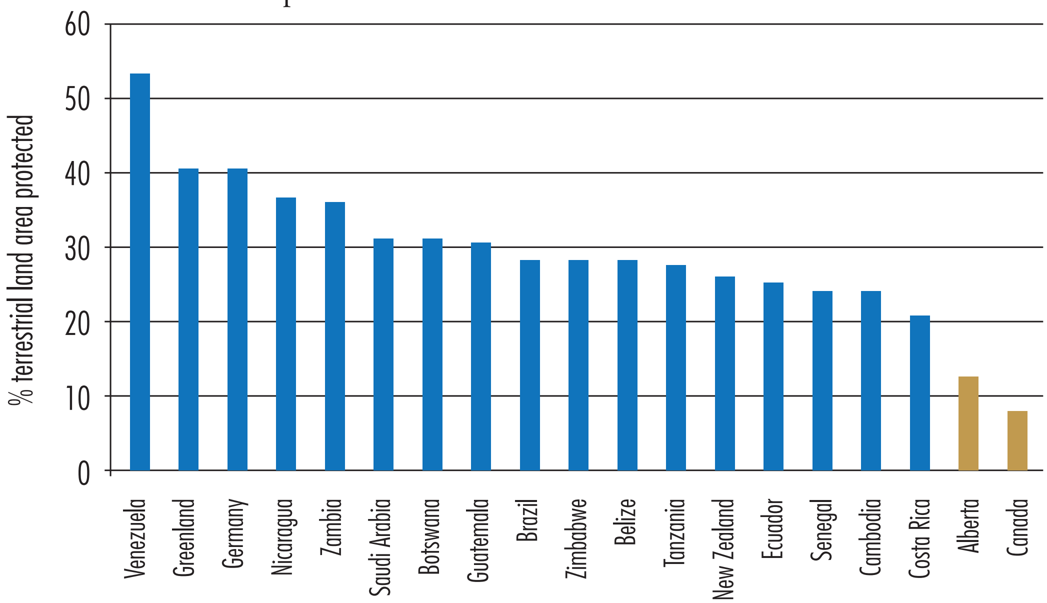


Figure 1. Selected world leaders in establishment of legislatively protected areas compared to Canada and Alberta[13]

LAIRP

The draft LAIRP document identifies approximately 11% of the region as new protected areas, which, when added to the 6.7% already protected, brings legislative protection to a total of only approximately 18% of the region.[11]

Unfortunately, it is clear that LAIRP conservation recommendations were led by avoidance of industrial commitments, not conservation science. Thus the protected areas recommended by LAIRP are skewed to the north of the Lower Athabasca region and are largely unrepresentative of the kinds of habitats that are being impacted by oilsands development. The LAIRP document also ignores many of the conservation sites proposed by the Regional Advisory Council charged with making recommendations for the Lower Athabasca region.

The draft LAIRP identifies 6% of the region as "ecosystem forestry" conservation areas that allow industrial logging.[12] These are not considered protected areas by the environmental community. All the proposed protected areas allow development of existing oil and gas leases.

more habitat for species and reduce the threat to biodiversity. Protected areas serve many roles. One important criteria for protected areas in the province relates to the habitat needs for woodland caribou, a threatened species in Alberta with declining populations.

The Cumulative Environmental Management Association (CEMA) recommended that between 20 and 40% of the Regional Municipality of Wood Buffalo be permanently protected from industrial activity. The Boreal Leadership Council, a group made up of leading resource development companies (including oilsands producer Suncor and forest company Alberta-Pacific Forest Industries) has recommended that 50% of Canada's boreal forest be permanently protected, while the remaining 50% of the forest be handled using world-class sustainable forest management practices.

While establishment of protected areas will close off future opportunities for oilsands and forestry development, a substantial increase in protected areas is economically viable. Research from the University of Alberta, sponsored by the Alberta Government's Land Use Secretariat, has shown that Alberta could permanently protect 40% of its public forests from industrial activity at a cost of only 3 to 7% of the net present value of natural resource development in Alberta.[14]

RECOMMENDATION

The Alberta Government should legislatively protect at least 50% of its public forest lands from industrial development. Protected areas should be developed and co-managed with Aboriginal peoples

Implement a wetlands and biodiversity offset policy

Unlike U.S. jurisdictions, Alberta has neither a wetland policy nor conservation offset policies for its forested areas. Biodiversity offsets should be required for upland and wetland habitats as best practice to mitigate project-specific impacts of developments.

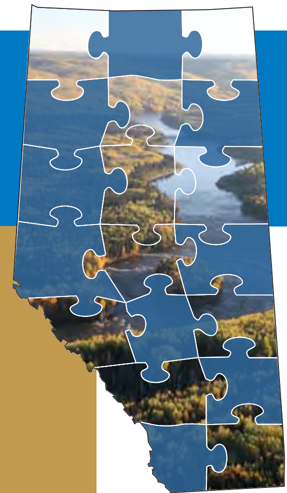
The Alberta Land Stewardship Act is enabling legislation that could support the establishment of biodiversity offsets. Alberta could make mandatory offsets for oilsands companies part of land use plans. Offsets should be area-based and could include additional wetland or forest restoration, conservation of environmentally significant private lands or the retirement of development tenures.

LAIRP

Alberta committed to development of a biodiversity offset program in its 2008 oilsands planning document *Responsible Actions*,[15] but has apparently not made any progress in implementing such a plan. While the advice from the Regional Advisory Council to the Government of Alberta recommended that the LAIRP should "Develop and implement land-use offsets for industrial development" and "Implement Alberta's new wetland policy once it is developed"[16] neither of these issues is mentioned in the draft plan.

RECOMMENDATION

Require establishment of biodiversity offsets for all oilsands development to offset impacts to all habitat types. To ensure a net positive environmental benefit and address existing cumulative effects, offsets should be established with a 3:1 offset ratio — three hectares of land should be conserved or restored for every hectare of new disturbance that occurs within the Boreal Forest Natural Region.



SOLVING the Puzzle

Land

Set maximum levels of development

Both oilsands mining and in situ oilsands development are intensive land uses. The Cumulative Environmental Management Association was mandated by the Government of Alberta to make recommendations on how to limit environmental impacts of oilsands development. The CEMA Terrestrial Ecosystem Management Framework recommended that limits be placed on the maximum amount of lands available for oilsands development at any time.[17] When adequate reclamation had been demonstrated, other areas could be opened to development.

In order to protect ecosystems, Pembina recommends as an interim threshold that no more than 5% of any planning area be under oilsands development at any time. CEMA recommended measuring "intensive area" as any quarter township (3 mile x 3 mile area) that included oilsands development, to account for the fragmentation associated with in situ oilsands development. A 5% interim disturbance limit would mean that for the 93,000 km^2 Lower Athabasca Area, no more than 4,600 km^2 of oilsands leases would be available for development at any time (The current area of oilsands leases in Northern Alberta is 85,000 km^2).[19]

LAIRP

The draft LAIRP plan does not set maximum levels of development but acknowledges that this work needs to be completed by 2013.[18] The commitment in the draft LAIRP hints that development targets may not be protective of the environment:

Develop a ***land disturbance plan*** *for public land in the Green Area for the Lower Athabasca Region by 2013. Features of the plan will include:*

Land disturbance limit(s) and pre-limit management triggers to address established biodiversity indicator targets in the biodiversity management framework. Setting of limits will involve stakeholders and integrate economic development and social needs. Limits will recognize that to meet economic outcomes, land disturbance is projected to increase substantially from current levels as oilsands are further developed.

RECOMMENDATION

Land use plans should mandate that no more than 5% of any Alberta planning region is available to oilsands development at any time.

Reform the approach to reclamation liability management

Until recently, the Alberta government held letters of credit to cover the cost of mine reclamation should companies default on their reclamation commitments. The Pembina Institute calculated that this older program did not collect adequate security, and that provincial taxpayers may be carrying an unaccounted liability of up to $15 billion. Inadequate security collection, along with transparency and accountability concerns, have been raised by the Alberta Auditor General for the past eleven years.

In March 2011, the Government of Alberta announced a new reclamation financial liability program, the result of closed-door collaboration with industry. While the new program is more transparent and accountable in the estimation of reclamation costs, it still places Alberta taxpayers and the environment at risk. The new program actually weakens security in the short to medium term by allowing companies to use undeveloped bitumen as an asset to offset their clean-up costs. While many of the companies involved in oilsands mining are financially solvent, they are highly vulnerable to changes in global oil prices and regulatory costs. As a result, if the price of oil dropped significantly or if new regulations made the industry uneconomic, this new approach would leave Alberta taxpayers liable for reclamation costs. The Alberta government should be risk-averse in its reclamation liability management, not risk-tolerant. Oilsands companies, not taxpayers, should provide sufficient security to cover all of the liabilities created by oilsands mining.

RECOMMENDATION

Develop a new, transparent and risk-averse mine security program that ensures the Alberta government collects financial security equivalent to the total liabilities created by oilsands extraction. Consequently, if an oilsands mine was unable to pay for reclamation, adequate funds would be available to complete all reclamation. Using the proposed asset-to-liability approach to oilsands reclamation is not appropriate and places taxpayers at risk.

LAIRP

The draft LAIRP document commits to:[20]

> *Implement the progressive reclamation strategy enhancing the suite of policies, strategies and reporting mechanisms used to drive progressive on-going reclamation of mining operations. The strategy includes an enhanced reclamation certification process, a transparent public reporting system for reclamation progress and a new progressive reclamation financial security program.*

The draft LAIRP commits to using a policy that does not collect security equivalent to the full cost of reclamation for oilsands mines.

The total liabilities created by oilsands mining must be covered by the amount of financial security collected.

PHOTO: DAVID DODGE, THE PEMBINA INSTITUTE

Conserve woodland caribou

All caribou herds in Alberta are considered non-self-sustaining. Declines in woodland caribou populations in Alberta are a symptom of inadequate land management policies and too-high levels of cumulative development.

Maintaining caribou populations requires maintaining sufficient caribou habitat. This can be achieved through a combination establishing large protected areas throughout caribou ranges in Alberta (see protected areas, above), setting maximum levels of development (see maximum levels of development) and aggressively restoring those caribou ranges that have already been impacted by decades of poorly-managed development (see biodiversity offsets, above).

The Alberta Caribou Committee, a body responsible for making recommendations on caribou conservation in Alberta, has developed management recommendations for the Lower Athabasca Region. These include establishing six conservation areas, thousands of square kilometres in size and free from industrial development, for caribou in northeastern Alberta.[21]

LAIRP

The draft LAIRP document does little to address caribou habitat needs, stating only that "A new biodiversity management framework for the Lower Athabasca Region…..will be developed by 2013 and will…. address caribou habitat needs in alignment with provincial caribou policy."[22]

The proposed protected areas identified in the LAIRP plan cover only 11% of the caribou range in the Lower Athabasca Region, substantially less than would be required to stabilize caribou population declines. As proposed, development of existing oil and gas leases would be allowed in all of these areas.

RECOMMENDATION

Follow the recommendations of the Alberta Caribou Committee and demonstrate that all caribou ranges in Alberta meet science-based objectives to maintain caribou populations through a combination of establishing protected areas, setting thresholds on maximum levels of development in caribou habitat, and establishing biodiversity offsets in caribou habitat.

Water

Protect the Athabasca River from water withdrawals during low flow periods

Oilsands mining operations divert substantial amounts of water from the Athabasca River, potentially placing pressure on aquatic ecosystems during low flow periods. Because diversions are largely permanent (only 3.3% of the water used in oilsands processing is returned to the river), a comprehensive water management plan is needed to ensure that current and future projected diversions protect aquatic ecosystems.

When too much water is diverted from a river system, water quality may change and fish habitat may decrease. On the lower Athabasca River, surface water withdrawals have a direct influence on flow, potentially reducing the available habitat during the low-flow periods common during winter months. In turn, surface winter withdrawals can jeopardize the overwintering survival of many fish and other aquatic species. The Athabasca River watershed and Peace-Athabasca Delta are critical to First Nations for hunting, fishing and gathering. In recent years, traditional resources from the river system have been more difficult to access due to lower flows.[23]

While efforts to establish water management planning have been initiated for the Lower Athabasca, they have failed in several respects. A 2007 joint water management framework announced by the Department of Fisheries and Oceans and Alberta Environment took a first step by establishing a plan to account for water demand and establish cumulative limits on withdrawals. But Phase 1 did not create an enforceable framework requiring companies to stop withdrawing water under the law, instead opting for a voluntary industry sharing arrangement. Of greater concern is the fact that two major oilsands companies are not subject to the management system as their licences have been effectively grandfathered leaving aquatic ecosystems vulnerable.[24]

Aboriginal communities remain concerned about the impact of lower water flows on access to culturally-significant places, travel on the river, and opportunities to pass culture and knowledge to future generations. Currently, there is no consensus around what constitutes an appropriate Ecosystem Base Flow (EBF) on the lower Athabasca river. While many stakeholders have agreed upon a flow target of 87 m^3/s this was not the consensus of all parties, and issues remain around the exemption of "legacy water rights holders".[25] A report prepared for the Athabasca Chipewyan

ECOSYSTEM BASE FLOW

An Ecosystem Base Flow (EBF) establishes a flow target in a river below which no withdrawals are permitted. An EBF is in place to ensure that there are no increases in the frequency and duration of very low flows which can affect habitat availability, food production, and water quality.[30]

and Mikisew Cree First Nations recommended the adoption of a precautionary flow level whereby no surface withdrawals would be allowed when the river flow drops below 100 m^3/s. This would require active management among all stakeholders.[26] This precautionary flow was recommended as a management tool until a more scientific consensus could be reached.[27] First Nations have also stated that additional studies are needed to fully consider the relationship between water flows, instream flow needs[28] and aboriginal water rights.[29]

By 2011, the problems of Phase 1 for the Athabasca Framework remain unresolved. While Government of Canada scientists have acknowledged the need to establish an Ecological Base Flow that would set an absolute cut-off for withdrawals, the voluntary system remains in place.[31] At the time of writing, the final Phase 2 water management framework has not yet been officially adopted, but there are concerns that the new framework will follow the voluntary approach used in Phase 1 and will continue to grandfather the rights for two existing oilsands companies.

The process to establish a water management plan goes back to the early 2000's when the Surface Water Working Group of the Cumulative Environmental Management Association was charged with the task of establishing the in-stream flow needs assessment for the lower Athabasca River. The assessment anticipated that by 2003, a water usage management system as well as criteria for water usage that protect science-based and social values would be in place in the lower Athabasca River. [32]

The draft LAIRP notes that "the Alberta government is committed to updating the surface water quantity management framework for the Lower Athabasca River by 2012."[33] It does not commit to ensuring that water withdrawals will be halted during low flow periods.

RECOMMENDATION

Alberta Environment should complete a water management plan that identifies a science-based Ecosystem Base Flow for the lower Athabasca River, as a low-flow threshold below which all water withdrawals would cease. The EBF should be legally enforceable, and all water permits issued by the Alberta Government at any one time should be accountable to meet that EBF. In the interim, the low-flow threshold for the lower Athabasca River should be at least 100 m^3/s.

Define sustainable groundwater yield for the Lower Athabasca region's groundwater management areas

While much attention has been focused on how oilsands mining operations affect surface water diversion from the Athabasca River, a potentially more challenging and equally troubling issue concerns oilsands impacts to groundwater. Groundwater moves relatively slowly and recharge rates for aquifers can range from days to tens of thousands of years.

Both mining and in situ oilsands production affects groundwater resources. Before mining operations can begin, the forest must be cleared and wetlands drained. The basal aquifer underlying the bitumen may need to be drained to prevent flooding into the mined areas. The elimination of the wetlands decreases groundwater recharge, and artificially-restored boreal wetlands are not yet capable of replicating this function.[34] The creation of tailings lakes covering hundreds of square kilometres also threatens groundwater quality as a result of potential seepage. Groundwater withdrawals from aquifers for in situ development can have an indirect influence on surface water flows. Groundwater discharge is likely an important contributor to the Athabasca River flows, particularly in the low-flow winter months.

While individual companies may try to predict how long it would take for an aquifer to recover from these withdrawals, groundwater impacts could still be significant because each project is assessed separately[35] and there is not yet a consideration of the cumulative impacts over the many-decade life span of multiple projects. Additionally, the complex geology of northern Alberta with buried valleys and channels increases the difficulty in understanding the connections between surface and groundwater.[36]

While mining operations use more water than in situ operations at this time, groundwater use for in situ operations will increase given that in situ development is growing even faster than mining. In the future, water use for in situ production could be as great as or greater than for mining unless new extraction processes are adopted that reduce or avoid the use of water.

The absence of an integrated regional groundwater framework in the region impacted by oilsands development requires the adoption of the precautionary principle to protect fresh aquifers. Dr. Jim Bruce, member of the Council of Canadian Academies' 2009 Expert Panel on Groundwater, has said that oilsands projects are providing a "completely inadequate understanding of the groundwater regime in the area" despite having a significant impact on groundwater.[37]

Some of the groundwater unknowns[38] include:

- how low-flow levels in the Athabasca River affect shallow groundwater;
- how increased oilsands operations dewater or reduce non-saline aquifer

supplies as well as depressure or dewater saline aquifers;

- how changes in water quality, resulting from aquifer disturbance and tailings-pond leakage, affect the quality of groundwater and surface water resources;
- what data are required to assess the claim that deep injection of steam and waste does not negatively impact the regional and local aquifer systems, and whether these data are available
- what regional threshold objectives should be to ensure sustainable groundwater management.

Some of these knowledge gaps were echoed by CEMA[39] in their 2010 groundwater quality study, a study that was acknowledged by the Royal Society of Canada report as a first step towards the establishment of a regional groundwater framework.[40]

While efforts are underway to develop a conceptual model of the hydrogeology of the Athabasca oilsands region,[41] more work is needed to create an integrated regional groundwater framework for the region. Groundwater concerns are currently only considered at the local scale; hydrogeological studies are conducted on a case-by-case basis[42] and thereby fail to consider cumulative effects. Furthermore, the often poorly-understood interaction between surface water and groundwater resources has traditionally meant that each component is managed as a separate resource. The management of water resources, both surface water and groundwater, needs to be based on an appropriate level of understanding of their interactive relationship in the hydrologic cycle. In the absence of a regional geological framework that can be used to assess this degree of interrelationship, it is appropriate to manage surface water and groundwater as a single resource.

The capacity of Lower Athabasca aquifers to deliver water in a sustainable way should be defined and determined. This concept of "sustainable yield"[43] for groundwater can aid in identifying a threshold to protect groundwater quantity and quality. A sustainable yield for groundwater should consider overall regional withdrawals with rates of recharge that will not compromise the quantity and quality of water-sustaining wetlands, lakes and rivers. In other words, groundwater limits should follow the hydrologic principles of mass balance, preparing for the possibility that there maybe much less groundwater available than anticipated under existing case-by-case approvals.[44]

RECOMMENDATION

Measure and map the quantity and quality of groundwater and surface/groundwater interactions, to determine both the short and long-term sustainable yield of non-saline groundwater in the Lower Athabasca's groundwater management areas. Set legal requirements to implement and enforce the sustainable yield of groundwater.

Ensure enforceable regulations are in place to protect non-saline groundwater resources

The primary source of water used for in situ oilsands operations is groundwater. In situ techniques require approximately 1.1 barrels of water to extract a barrel of bitumen.[45] In 2010, in situ industry water consumption was approximately 17 million m^3 per year of fresh surface or groundwater, and that amount is expected to increase to 22 million m^3 per year by 2015.[46] Restrictions that would limit freshwater use by in situ operations have yet to be implemented.[47] The amount of groundwater available for bitumen extraction is unknown and as a result, the quantitative impact of extraction on regional groundwater reserves is also unknown.[48]

The current policy framework related to groundwater use by the oil sector remains inadequate in light of the unknowns around the availability of non-saline groundwater. In 2005, the Alberta Government adopted the Water Conservation and Allocation Policy for Oilfield Injection to reduce or eliminate the use of fresh water for enhanced oil recovery and in situ operations.[49] At present, most in situ projects are not in "water short" or "potentially water short" areas and the volume of water that they will be permitted to use depends in part on weighing the economic costs of alternatives. This policy is currently under review, however currently appears to favour economic criteria.[50]

Alberta Environment and the Energy Resources Conservation Board (ERCB) developed a draft directive in 2009 that would require in situ operators to minimize their use of fresh water by evaluating alternatives when possible.[51] Larger operators would be required to recycle water to reach a maximum of 10 percent of annual water to be fresh water.

The Water Conservation and Allocation Guideline for Oilfield Injection relies on the discretion of the director to some extent,[52] while the draft ERCB directive is not yet in force and appears to be stalled.

LAIRP

The draft LAIRP does propose a Groundwater Management Framework for the Lower Athabasca Region. However, the draft LAIRP does not include environmental limits for groundwater quantity at this time.[56] The draft LAIRP also excludes groundwater having a mineralization of 4,000 mg/l TDS or greater.

Given the uncertainty about the sustainability of using non-saline groundwater resources, companies must be required to seek alternatives in a timely fashion. For this reason, Alberta Environment must carefully evaluate the findings of its current review of the Policy and Guideline as they affect in situ operations, to determine to whether more stringent requirements are necessary. Alberta Environment should ensure that the guideline and draft ERCB directive are updated to the extent indicated by the review, and that the revised directive is implemented as soon as possible and strictly enforced.

Alberta Environment defines saline water as water that contains more than 4,000 milligrams per litre of total dissolved solids (mg/l TDS).[53] This level was set to include all groundwater that is expected to be potentially useable by the public in the future with reasonable levels of treatment. A higher cutoff is desirable as more complex treatment technology is possible in extreme water shortage situations. For example, the U.S. has a much more stringent standard and protects certain underground sources up to 10,000 mg/l TDS to ensure an adequate supply for present and future generations.[54] In the Lower Athabasca region, shallower bedrock aquifers have TDS values from 1,000 to 4,000 mg/l, with the deeper formations (Basal McMurray and Methy formations) generally having saline conditions (4,000 to greater than 300,000 mg/l TDS).[55]

RECOMMENDATION

Ensure enforceable regulations are in place to protect non-saline groundwater resources by updating and implementing existing guidelines and definitions and requiring companies to seek alternatives to non-saline groundwater. To protect more of our finite water resources, the Alberta government should expand its definition of regulated groundwater from the current level of water containing less than 4,000 mg/l of total dissolved solids (or TDS, a measurement of mineral, salt and metal content) to include water with up to 10,000 mg/l TDS.[57] Operators should explicitly detail the efforts made in design to minimize environmental trade-offs between reducing use of non-saline water and increasing water treatment needs, which could potentially result in increased waste, energy use and greenhouse gas emissions.

Require technology that eliminates wet tailings production

Tailings lakes, which now cover an area the size of the City of Vancouver or Washington, D.C., are projected to grow by 30% in the next decade — from 843 million cubic metres in 2010 to over 1.1 billion cubic metres in 2020.[58] Containing a host of toxic compounds, tailings lakes pose an ongoing threat to surface water and groundwater through seepage, represent a significant public liability, and poses a mortality risk to waterfowl.

Political and industry leaders have recognized the liability of tailings on the landscape. In April 2010, Alberta Premier Ed Stelmach stated his objective to eliminate wet tailings ponds within "a few years."[59] Retired Shell Canada CEO Clive Mather said it is time the industry moved to eliminate tailings.[60] Nevertheless, technology and regulatory oversight has not kept pace with the growing volume of toxic tailings on the landscape. A weak regulatory framework providing inadequate incentives to further advance commercialized technology has contributed to the failure to eliminate wet tailings from the landscape.

The technology of choice for the past 15 years has been consolidated tailings or non-segregating tailings (CT/NST), a process that helps free up a fraction of the tailings water to be recycled for plant use and reduce the overall volume of mature fine tailings (MFT) contained in the lake. Because the CT/NST process requires a significant amount of sand, and the sand is also required to build containment for the released and recycled water, the success of CT as a means to substantially reduce the volume of toxic tailings has been limited.

While there has never been a complete reclamation of a tailings lake, existing technology and regulation suggests progress has been made. Recently, Suncor announced that it is planning to adopt a new approach called Tailings Reduction Operations (TRO), a drying process that converts fluid fine tailings more rapidly into a solid landscape suitable for reclamation. If successful, the technology could enable Suncor to clean up existing tailings waste and significantly

LAIRP

The draft LAIRP does not specifically commit to eliminate wet tailings production. The plan notes:[68]

> *Government of Alberta will establish a tailings management framework for mineable oilsands operations by 2012. The framework will provide guidance on managing tailings to provide assurance that fluid fine tailings will be reclaimed as quickly as possible, and that legacy (current) inventories will be reduced. The framework will establish regional limits, as well as a focus on the development and implementation of new technologies over the next ten years.*

reduce the legacy volume of end-of-mine fine tailings to 75 Mm^3 versus the 108 Mm^3 that would have resulted from the previous CT technology. The area of Suncor's end-pit lake could end up being reduced from 14 km^2 to 8.4 km^2.[61] According to Suncor, the TRO technology has enabled it to cancel plans for five additional tailings ponds at existing mine operations.[62],[63]

Regulatory compliance could clearly act as a major impetus toward the adoption and commercialization of new technology. This was thought to be the case when Alberta's Energy Resources and Conservation Board (ERCB) announced Directive 74 in 2009 to regulate the reclamation of tailings waste. The directive requires oilsands companies to submit tailings management plans,[64] and stipulated that by June 30, 2013, oilsands operators are to divert at least 50% of the fine particles in their ore to a dedicated disposal area with a solid surface strength of 5kPa in the first year and 10kPa after five years.

Unfortunately, the ERCB stopped short of requiring full compliance with the regulation. Only two of the nine current oilsands projects met the requirements.

While significant research has already been dedicated to reducing or eliminating toxic tailings, it is clear that far more is needed to ensure that tailings management and water conservation technology keeps pace with increasing production. This means making the needed capital investments in research and technology development to advance these practices to a commercial scale. In December 2010, seven companies[65] announced a collaborative approach towards sharing information on research and development as well as technology.[66]

The Royal Society of Canada has noted, "Technologies for improved tailings management are emerging but the rate of improvement has not prevented a growing inventory of tailings ponds. Reclamation and management options for wet landscapes derived from tailings ponds have been researched but are not adequately demonstrated."[67]

Government will need to send strong regulatory signals to promote the needed technology advancements to eliminate wet tailings accumulation and ultimately remediate existing tailings accumulations. All of this needs to be underpinned by a regulatory system that is viewed as strict and consistent.

RECOMMENDATION

New mines should not be approved until the operation adopts a proven technology that eliminates the creation of wet tailings. In the interim, all current mines must be required to conform to the new tailings rules.

Prohibit water capping of fine tailings as a long-term reclamation solution

One proposed solution to the tailings problem has been to cap fine tailings with water in an end pit lake (EPL) at the end of mine life. Operators would deposit tailings waste into the last mine pit and cap it with fresh water from the Athabasca River.[69] End pit lakes are proposed to remain a permanent feature of the reclaimed landscape even though it has not been demonstrated that a pit that contains many millions of cubic metres of toxic tailings at the bottom can support a sustainable aquatic ecosystem. While at least 27 EPLs are planned over the next 60 years, a fully realized EPL has yet to be constructed.[70]

There continues to be much uncertainty related to issues of salinity, retention time, groundwater recharge and discharge rates, EPL limnology, and the chronic toxicity of oilsands process-affected water and its constituents. Given the extreme uncertainty, it is prudent to reject water capping of fine tailings as an acceptable oilsands reclamation strategy.

LAIRP

The draft LAIRP does not prohibit water capping of fine tailings as a long-term reclamation solution. The draft plan notes:[71]

> *Government of Alberta will establish a tailings management framework for mineable oilsands operations by 2012. The framework will provide guidance on managing tailings to provide assurance that fluid fine tailings will be reclaimed as quickly as possible, and that legacy (current) inventories will be reduced. The framework will establish regional limits, as well as a focus on the development and implementation of new technologies over the next ten years.*

RECOMMENDATION

Mine applications that propose the storage of MFT under end pit lakes as their reclamation strategy should not be approved. Existing operations with approved end pit lake plans should be modified to eliminate the need for end pit lakes as long-term storage sites for toxic tailings waste.

Air

The mining or in situ extraction of bitumen from oilsands, and the upgrading of bitumen into synthetic crude oil, are very energy intensive and involve processes that generate significant air emissions. These processes include fossil fuel combustion to produce steam, and in some cases electricity;[72] bitumen separation using solvents that are subsequently emitted from tailings ponds; diesel exhaust emissions associated the large mine fleets; sulphur recovery when bitumen is upgraded, resulting in production of sour gas; and numerous other bitumen and water storage and treatment processes that have fugitive emissions which can be significant for a large facility. Flares and diverter stacks used to deal with emergency and upset conditions can also be a significant source of air contaminant emissions.

Oilsands operations lead to increases in air pollutants including sulphur oxides (SO_x), nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), volatile organic compounds (VOCs), ozone (O_3) as a result of NO_x and VOC emissions, polynuclear aromatic hydrocarbons (PAHs), and airborne mercury. The emissions produced by oilsands operations are predicted to increase significantly over the next decade.[73] As summarized in Table 1, elevated levels of SO_x and NO_x could lead to smog, acid rain, and the acidification of soils and surface waters, which in turn poses risks to human health. See Appendix A for more information on the impacts from air emissions from oilsands development.

Acidifying emissions from oilsands development may pose a risk to northern lakes.

PHOTO: DAVID DODGE, THE PEMBINA INSTITUTE

Implement world-class air quality standards

The current Alberta Ambient Air Quality Objectives (AAAQO) while intended to provide protection of the environment and human health, do so only to the extent deemed technically and economically feasible, as well as socially and politically acceptable.[74] In this regard Alberta Environment has indicated that “AAQOs are often a compromise between science and achievability. They are not entirely protective of human health and/or the ecosystem and, importantly, they are not a safe level that can be polluted up to.”[75] As a result, Alberta standards are less stringent than those of the European Union, U.S. Environmental Protection Agency and World Health Organization for what qualifies as an “exceedance” or “poor air quality”. Compared with guidelines established by the World Health Organization, AAAQOs permit higher concentrations of particulate matter, double the hourly-average concentrations of NO_x, and over seven times the daily-maximum concentrations for SO_2.[76]

Table 1. Air quality criteria from various jurisdictions

Parameter	Averaging Time	Air quality criteria in noted jurisdiction[a] (ug/m^3)[b]			
		Alberta Environment (objectives or guidelines)	USEPA (standards)	WHO (guidelines)	European Union (targets, limits or objectives)[c]
Sulphur Dioxide (SO_2)	10 minute	no criteria	no criteria	500	no criteria
	1 hour	450	196 (3 year average of the 99%tile of maximum daily values in a year)	no criteria	350 (not to be exceeded more than 24 times in a calendar year)
	24 hour (daily)	125	no criteria	20	125 (Not to be exceeded more than 3 times in a calendar year)
	30 days	30	no criteria	no criteria	no criteria
	Annual	20	no criteria	no criteria	20
Nitrogen Dioxide (NO_2)	1 hour	400	188 (3 year average of the 98%tile of maximum daily values in a year)	200	200 (not to be exceeded more than 18 times in a calendar year)
	24 hour	200	no criteria	no criteria	no criteria
	annual	60	100	40	40

Parameter	Averaging Time	Air quality criteria in noted jurisdiction[a] (ug/m³)[b]			
		Alberta Environment (objectives or guidelines)	USEPA (standards)	WHO (guidelines)	European Union (targets, limits or objectives)[c]
Ozone (O_3)	1 hour	160	no criteria	no criteria	no criteria
	8 hour	128 (4th highest measurement annually averaged over 3 consecutive years)	147 (4th highest measurement annually averaged over 3 consecutive years) under review	100	120 (from 2010 not to be exceeded more than 25 days per calendar year averaged over 3 years) 120 (from 2020)
Carbon Monoxide (CO)	15 minutes	no criteria	no criteria	100,000	no criteria
	30 minutes	no criteria	no criteria	60,000	no criteria
	1 hour	15,000	40,000	30,000	no criteria
	8 hours	6,000	10,000	10,000	10,000
Particulate Matter ($PM_{2.5}$)	1 hour	80	no criteria	no criteria	no criteria
	24 hour	30	35 (3-year average of the 98th percentile of 24-hour values)	25 (a 99%tile value of maximum daily values (i.e. 3 days a year can have values >25)	no criteria
	annual	no criteria	15 (3 year average)	10	25 (effective 2015) and 20 (effective 2020)
Hydrogen Sulphide (H_2S) or Total Reduced Sulphur (TRS)	30 minute	no criteria	no criteria	no criteria	no criteria
	1 hour	14 (for H_2S but also applied to TRS)	no criteria	no criteria	no criteria
	24 hour	4 (for H_2S but also applied to TRS)	no criteria	no criteria	no criteria

[a] *Criteria as of September 2010 except for Alberta Environment which is as of December 2010*

[b] *All values converted to ug/m³ with most at 1 atm and 25°C*

[c] *EU values at 20°C*

LAIRP

The draft LAIRP includes an air quality management framework that identifies potential limits for NO_2 and SO_2. The framework proposes strengthening the current ambient air quality objectives for these pollutants. The LAIRP does not propose new management frameworks for other pollutants such as VOCs, PAHs and particulate matter. While the air quality management framework identifies four "trigger" levels for managing air emissions, the management actions proposed are relatively weak until Level 4 is reached. The framework does not appear to strive for good or improving air quality, merely avoiding unacceptable levels.

However, it should be acknowledged that the LAIRP air quality management framework does introduce some improvements to the current management of air quality in the region. The framework specifies that exceedances of AAAQOs will continue to be managed in the same way, externally and independent from the LAIRP process. New triggers for short-term air quality management are presented in the draft LAIRP that would serve as an additional tool to the existing air quality objectives.

In addition, the LAIRP air quality management framework states that it intends to incorporate any changes to the AAAQOs, using any improved air quality objectives as the limit for the annual triggers. The draft plan includes limits based on proposed updates to the AAAQO for NO_2 annual and hourly averages. While this update to the AAAQO has not yet been implemented, it would represent a considerable improvement compared with the current values and a positive step towards the health guidelines recommended by the World Health Organization. See Table 2 below for a comparison of the proposed changes.

Table 2: Proposed updates to the AAAQO for NO_2 (2011)

Averaging Time	Current AAAQO (μg/m³)	Proposed AAAQO (μg/m³)	Relative Improvement	WHO guidelines (μg/m³)
1 hour	400	300	25%	200
Annual	60	45	25%	40

The WHO Air Quality Guidelines (AQG) represent the most up to date and widely agreed-upon assessment of health effects of air pollution, recommending targets for air quality at which the health risks are significantly reduced.[77] The WHO AQG are intended to be relevant and applicable worldwide and to provide clear health-based recommendations on the targets for air pollution reduction.[78] The recent U.S. EPA National Ambient Air Quality Standards for NO_2 and SO_2 are consistent with the maximum 1-hour limits for these pollutants.[79],[80] Regulating emissions at higher allowable concentrations than the WHO guidelines puts the health of Albertans at risk and limits the creation of a credible environmental management system for the oilsands.

Even with the higher allowable concentrations in Alberta, the AAAQOs were frequently exceeded by oilsands operators in recent years — with an increasing trend.[81] In 2009, the AAQOs were exceeded 1,556 times in 2009 in the Athabasca region, up from 47 times in 2004.[82] These exceedences were largely related to hydrogen sulphide/reduced sulphur emissions and provide an indication of the air quality issues that can result if emissions are not properly managed.

RECOMMENDATION

Establish air emission limits to achieve the World Health Organization's Air Quality Guidelines to protect air quality and human health. Implement a progressive, multi-tiered system that requires varying degrees of action to prevent degradation of ambient air. This includes:

- Adopt the World Health Organization's Air Quality Guidelines for NO_x of 40 μg/m^3 (annual) and 200 μg/m^3 (hourly)
- Adopt the World Health Organization's Air Quality Guidelines for SO_2 of of 20 μg/m^3 per 24 hours and the EU 1-hour guidelines for SO_2 of 350 μg/m^3
- Adopt the World Health Organization's Air Quality Guidelines for $PM_{2.5}$ of 25 μg/m^3 per 24 hours.

Large trucks used for mining are the primary source of NO_x emissions in the oilsands

PHOTO: C. CAMPBELL, THE PEMBINA INSTITUTE

Require best available technology to address air emissions

Good air quality depends in large part on how effectively air emissions are controlled and managed. It is not unreasonable for Albertans to expect that oilsands operators will employ the best available emission control technologies at new projects and that existing operations will strive for continuous reductions in emissions. Unfortunately this is not the case: Alberta does not currently require best available technologies to reduce air emissions associated with oilsands development. Alberta Environment has an Industrial Release Limits Policy[83] that has as one of its principles:

"Industrial release limits will be established based on limits achievable using the most effective demonstrated pollution prevention/control technologies ..."

This policy needs to be rigorously applied to the oilsands industry.

In some cases, policies cite targets that should either be converted into enforceable requirements or limits, or at a minimum, be aggressively applied as opposed to being totally voluntary. For example, large boilers, heaters and turbines used in the oilsands industry are significant sources of emissions. There is currently a policy[84] aimed at improving

the emissions rates from these types of equipment. The policy outlines Performance Targets based on best available technologies that are "economically achievable" but then only really requires companies to meet the significantly lower Compliance Limits.

In other cases there is simply no policy in place to ensure that oilsands facilities are using the best equipment available and updating this equipment regularly as improvements are made available on the market. For instance, the large trucks used for mining are the primary source of NO_x emissions in the oilsands. However, many of the trucks currently in operation are older models with significantly higher rates of emissions. While retrofits, upgrades and new models are available that would result in a significant decrease in emissions, there is no requirement in place to upgrade or replace this equipment. In fact, outside of the oilsands approval process, which has the ability to mandate equipment for one project at the time of approval, there is no requirement for new oilsands development to start with the best available technologies and no requirement for continuous improvement through retrofits.

The environmental community has outlined 11 opportunities for higher performance standards for oilsands operations including higher standards for sulphur recovery, Tier 4 standards for NO_x emissions by mine trucks, and controls on particulate emissions. For more information see Appendix B.

RECOMMENDATION

Require oilsands operations to use equipment with the lowest achievable emissions or to deploy best-available technology for air emissions reductions.

Greenhouse gases

Set science-based greenhouse gas reduction targets

The oilsands are the fastest growing industrial source of greenhouse gas (GHG) emissions in Canada.[85] As shown in Figure 2 below, the oilsands sector's GHG emissions more than doubled between 1990 and 2008 and emissions are forecast to double again between 2008 and 2020.

While the oilsands sector was able to reduce its GHG emissions intensity (emissions per barrel) by 39% between 1990 and 2006,[87] the rate of performance improvement has stalled in recent years. Much of the past improvement resulted from "low-hanging fruit" opportunities that have already largely been exploited, such as fuel switching (from more carbon-intensive coke to natural gas) and energy efficiency increases through cogeneration of heat and electricity. Furthermore, an increasing proportion of oilsands production is forecast to come from in situ techniques[88] which result in significantly higher GHG emissions per barrel of bitumen produced.[89]

One recent report did conclude that new innovations will enable oilsands emissions intensities to continue a declining trend; the report also projects that absolute oilsands emissions levels will increase as a result of the rapid pace of oilsands growth.[90] According to industry projections, under business-as-usual conditions, oilsands production could nearly triple in the next 15 years.[91]

There is now a broad scientific consensus that a global temperature rise of more than 2°C above the pre-industrial level would constitute a dangerous level

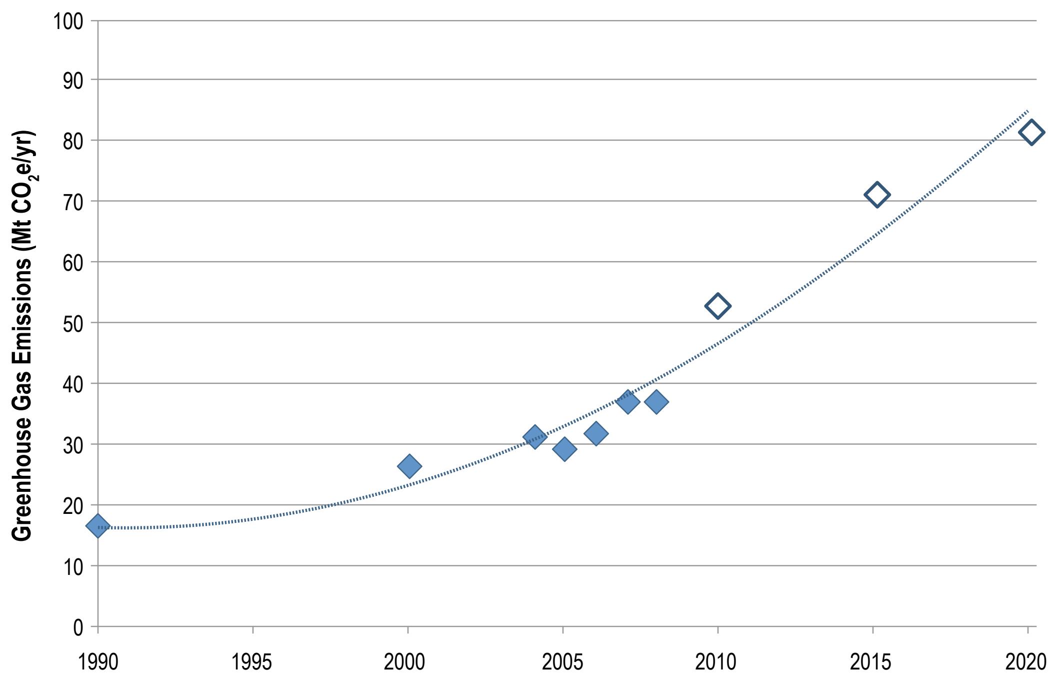


Figure 2: Historical and projected oilsands greenhouse gas emissions[86]

of climate change. Along with other G8 leaders, Canada accepted this 2°C limit at the G8 meeting in L'Aquila, Italy in 2009.[92] The Government of Canada re-affirmed its commitment to a 2°C limit by supporting the Copenhagen Accord and the Cancun Agreements[93] at the United Nations climate change conferences in 2009 and 2010 respectively. Analysis published by the Intergovernmental Panel on Climate Change, the world's leading climate science body, has shown that to have a reasonable chance of not exceeding the 2°C limit, industrialized countries should reduce their combined GHG emissions to 25 to 40% below the 1990 level by 2020, if they are to make a fair contribution to the necessary cuts in global emissions.

RECOMMENDATION

Commit to an Alberta greenhouse gas emissions reduction target consistent with a fair Alberta contribution to preventing dangerous levels of global warming (defined as keeping the global average temperature increase well below 2°C, relative to the pre-industrial level). Alberta's targets should include near-term, mid-term and longer-term (2050) goals.

Absolute oilsands emissions levels are predicted to increase as a result of the rapid pace of oilsands growth.

PHOTO: JENNIFER GRANT, THE PEMBINA INSTITUTE

Place an appropriate price on greenhouse gas pollution to drive emission reductions

The Pembina Institute has explored what policies would be required to achieve this level of reductions in GHG emissions for Canada as a whole, and what the ramifications would be for Alberta and the oilsands in achieving this target. The economic modelling firm MK Jaccard and Associates has conducted modelling that shows it is possible for Canada to reduce its GHG emissions to 25% below the 1990 level by 2020 through the implementation of an appropriate national price on GHG emissions and a package of other policy measures.[94]

Alberta can demonstrate leadership by supporting a high enough carbon[95] price that will drive significant reductions in greenhouse gas emissions. While a Canada-wide (or broader) price on greenhouse gas emissions is more economically efficient, provincial initiatives can make an important contribution in the absence of federal leadership on carbon pricing.

Even under the ambitious emission-reduction policy scenario modelled in the report, Alberta's economy still grows faster than that of any other province in Canada, with GDP growth of 38% from 2010 to 2020 (compared to a national average GDP growth of 23% from 2010 to 2020).[96] During this period, oilsands production grows to approximately 2.5 million barrels per day even while Canada meets an ambitious, science-based emission reduction target.[97]

RECOMMENDATION

Implement a carbon dioxide equivalent (CO_2e) emissions price, as either a full auction cap-and-trade system or a carbon tax covering all combustion and almost all fixed process emissions (i.e., covering the vast majority of Alberta's emissions). In order to incent adequate emission reductions, the emissions price should be approximately \$50/tonne CO_2e in 2010 and reach about \$200/tonne by 2020. If Alberta adopts a cap-and-trade system, these price levels can be achieved by tightening the cap over time; if Alberta implements a carbon tax, the tax level should rise on a predictable schedule that is transparently communicated in advance.

Require carbon capture and storage for oilsands operations

Requiring carbon capture and storage (CCS) for oilsands operations helps to moderate the carbon price level for the rest of Alberta's economy. Requiring CCS also spurs faster development of the technology, which helps reduce the costs of further CCS deployment by encouraging technological innovation.

RECOMMENDATION

Mandate the use of capture and storage technology to capture greenhouse gas emissions from all major new industrial sources by 2016. This would apply to: all formation CO_2 from new natural gas processors; all process CO_2 from new hydrogen production facilities; and all combustion CO_2 from all new coal fired electricity plants, oilsands facilities, and upgraders.

CO_2 from the upgrading process should be captured and stored.

PHOTO: DAVID DODGE, THE PEMBINA INSTITUTE

Monitoring

Effective monitoring is a crucial to inform responsible management of oilsands development. There has been substantial criticism of the current approach and level of monitoring.

The Pembina Institute has submitted detailed recommendations about what elements are required for effective and rigorous monitoring. These include elements such as program design and governance, meaningful stakeholder representation, resourcing, transparency, rigour, comprehensiveness and the ability to inform decision-making. Our recommendations to enhance monitoring of biodiversity, air, surface and groundwater are outlined here.

LAIRP

The draft LAIRP plan notes that Alberta is currently undertaking a review of its environmental monitoring, evaluation and reporting systems: [98]

In order to understand the effectiveness of Alberta's environmental management tools, the region's air, water, land and biodiversity are monitored, evaluated and reported on. Monitoring initiatives in the region include the Wood Buffalo Environmental Association, the Lakeland Industrial Community Association, the Regional Aquatics Monitoring Program and the Alberta Biodiversity Monitoring Institute.

There is significant investment in environmental monitoring systems in the Lower Athabasca Region, including systems for air, surface water, groundwater, land and biodiversity. Alberta is currently undertaking a review of environmental monitoring, evaluation and reporting systems. Recommendations from the Provincial Environmental Monitoring Panel are expected in 2011 regarding the development of an integrated, world-class monitoring system for the Lower Athabasca River, encompassing both the condition of the river and effects of development on the river, as well as recommendations on how the system can be expanded to all media in the region and to the entire province.

Develop a world-class biodiversity monitoring system

The existing Alberta Biodiversity Monitoring Institute (ABMI) has the potential to be a world-class monitoring system for biodiversity. Unlike other environmental media, where substantial changes to governance and rigour of monitoring programs are required, the major limitation of ABMI is currently a lack of funding to enable it to deliver its mandate of providing effective biodiversity monitoring information for Alberta.

The ABMI includes many of the elements of a rigorous monitoring program, including a rigorous, university-led scientific design plus value-neutral, arm's-length and publicly-accessible data and knowledge products.

However, ABMI only receives funds to cover about one-quarter of its full operating costs. The Government of Alberta has provided significant initial start-up resources to the ABMI, but funding has not been adequate for full delivery of the program. Full funding of the ABMI is an essential missing element of responsible development in Alberta.

RECOMMENDATION

Ensure full funding of the the Alberta Biodiversity Monitoring Institute, either directly from government or through an equitable funding model that requires all natural resource developers who impact biodiversity to contribute as a mandatory component of the regulatory approval process.

The cumulative impact of many typesof development affects biodiversity.

PHOTO: DAVID DODGE, THE PEMBINA INSTITUTE

Develop a world-class air monitoring system

The Wood Buffalo Environmental Association (WBEA) monitors ambient air quality for industry compliance and community air quality, terrestrial ecosystem effects and human exposure. WBEA has many of the features necessary in an effective air-monitoring program. WBEA data collection is transparent, is conducted by qualified technicians, uses appropriate equipment, and undergoes quality control verifications. The majority of WBEA data is publicly accessible online — downloadable in raw data formats by monitoring station or summarized in annual reports. Some of the passive sampler data is not easily accessible to the public. New monitoring projects are designed by qualified scientists and reviewed by an external third party.

WBEA data is limited by the size of the air quality monitoring network and the sub-optimal placement of monitoring stations. However, the WBEA monitoring program has insufficient funding to improve the network in a meaningful way. Currently, the majority of the funding for WBEA is provided directly by industry. This itself is not a concern; however, industry members have direct control on budget and other key decisions which are made through a multi-stakeholder consensus-based approach. WBEA membership is currently by organization, not by sector. Each company may have their own representative on the WBEA Board and as a result, industry members significantly outnumber other stakeholder members.

RECOMMENDATION

Expand air monitoring to meet scientific needs. Monitoring design should be developed through a consensus-based approach with full stakeholder input, with government implementing final decisions. To prevent a direct conflict of interest, the associated budget and funding mechanism should be developed by the Government of Alberta utilizing a 'polluter pay' approach. Provision of fees should be mandatory.

Develop a world-class water monitoring system

The current approach to monitoring oilsands impacts on water has now been widely discredited. Most recently, Environment Canada and a team of independent experts concluded that the current monitoring system for the Athabasca region “did not deliver data of sufficient quantity or quality to detect or quantify the effects of oilsands development.”[99] This is the sixth critical review of the state of aquatic monitoring since December 2010.[100]

RECOMMENDATION

Disband and replace the Regional Aquatics Monitoring Program (RAMP) with a comprehensive, scientifically robust monitoring system that is adequately resourced and free of industry influence.

Groundwater monitoring needs to be in place to gain a better understanding of the cumulative impacts of withdrawals from aquifers (both fresh and saline) and the relationship between groundwater and surface water. To date, monitoring for groundwater quality in the oilsands region as a whole has yet to be done, although work is underway to create a framework.[101] Monitoring is in place for project-specific needs of in situ operators; however, the cumulative effects of in situ operations are unknown, largely because the supply and quality of groundwater for the oilsands region is unknown.[102]

RECOMMENDATION

Make a long-term commitment to fund a regional monitoring network to monitor and assess trends in groundwater levels and groundwater quality indicators.

Appendix A Impacts from air emissions

Table 3: Effects of key oilsands pollutants on human health and the environment

Pollutant	Principal sources	Environmental impact	Health impact
Sulphur oxides[103]	Produced gas from in situ operations, burning of petroleum coke, extraction and upgrading for mining, sulfur in diesel fuel.	Is a major component of acid rain Contributes to the formation of smog and haze	At high levels can cause premature death, increased respiratory symptoms and disease, decreased lung function, as well as alterations in lung tissue and structure, and in respiratory tract defence mechanisms[104]
Nitrogen oxides[105]	Exhaust of mine fleet and burning of gas for boilers and heaters	Is a major component of acid rain, which can[106] leach essential nutrients from the soil and thereby negatively affect health and rate of growth of trees, reduce capacity of lakes and soil to neutralize acids and potentially change the pH condition of lakes and soil	Irritates the lungs and increases susceptibility to respiratory infections[107] Combines with VOCs in the presence of sunlight to form ground-level ozone, which can cause damage to human health[108]
Fine Particulate Matter[109]	Solid and liquid airborne particles emitted from fleet exhaust and combustion of all fossil fuels	Is composed of organic and elemental carbon particles from combustion of fossil fuels as well as sulphur and nitrogen compounds that can contribute to acid deposition Contributes to the formation of smog and haze	Can be carried deep into the lungs Has been linked with heart and lung problems such as asthma, bronchitis and emphysema[110] Strong links between high levels of airborne sulphate particles and increased hospital admissions for heart and respiratory problems, and higher death rates from these ailments[111]
Volatile Organic Compounds[112]	Evaporate readily from tailings ponds Venting of solution gas and unloading/loading of tanks. Fugitive emissions	Can combine with NO_x in the presence of sunlight to form ground-level ozone[113] Contributes to the formation of smog and haze.	Individual VOCs can be toxic to humans Benzene is a VOC emitted by oilsands operations. It is carcinogenic to humans and a non-threshold toxicant, which means that there is some probability of harm at any level of exposure[114]
Mercury[115]	Combustion of petroleum coke.	Airborne mercury can deposit and accumulate in streams, lakes, or estuaries, where it can be converted to methylmercury through microbial activity. Methylmercury accumulates in fish at levels that may harm the fish and the other animals that eat them.	Mercury, at high levels, may damage the brain, kidneys, and developing fetus.

Appendix B Recommendations for equipment emissions standards

- ❑ Implement the emissions rates outlined in the Alberta Environment Policy 2 performance targets as a required standard.[116]
- ❑ Implement the USEPA Tier 4 limits for the control of all emissions of air pollution from nonroad diesel engines and immediately engage the USEPA in discussions regarding a review of the Tier 4 NO_x limit for mobile sources greater than 750 hp.[117]
- ❑ Require units that emit more than 100 tonnes/yr of NO_x to meet emissions reduction rates equivalent to what would be achieved if they were required to install selective catalytic reduction controls.
- ❑ Employ stricter requirements under ERCB Directive 2001-3 for the smaller range of emission sources in this category. Units with inlet sulphur levels in the 1-5 tonnes per day size category should be required to meet a SO_x recovery rate of 90%.
- ❑ Ensure flared emissions are included in calculations of sulphur recovery rates from all sulphur recovery units and that their emissions rates still meet the given standards.
- ❑ Set a limit on the sulphur content of any gaseous fuel combusted in boilers, heaters and turbines.[118]
- ❑ Extend the AENV Policy 1B NO_x and SO_2 limits for new and retrofit boilers and heaters burning non-gaseous fuels to the whole oilsands industry, including those operations that burn and recycle coke as a part of bitumen upgrading.
- ❑ Apply PM controls (e.g. fabric filters/ baghouses or electrostatic precipitators) if primary PM emissions from a process unit are significant.
- ❑ Ensure all major stationary primary particulate emission sources are required to measure and report their condensable PM emissions.
- ❑ Reduce the ERCB limit on solvent releases to tailing ponds from 4 bbl/1000 bbl of bitumen to 3 bbl/1000 bbl by 2015.
- ❑ Ensure all operators are required to undertake a detailed and ongoing emission characterization and quantification monitoring program for their tailings ponds.

Appendix C Oilsands report summary

Since 2005, the Pembina Institute has completed over 40 reports that address management of the oilsands. All Pembina Institute reports include detailed recommendations to improve management of the oilsands. For more detailed background information on any of the recommendations in this document, please review the following publications.

2011

Developing an environmental monitoring system for Alberta
http://pubs.pembina.org/reports/alberta-oilsands-monitoring-submission.pdf

Life cycle assessments of oilsands greenhouse gas emissions
http://pubs.pembina.org/reports/pembina-lca-checklist.pdf

The uncertain prospect of oilsands exports to Asia
http://pubs.pembina.org/reports/pipelinetonowhere-usbriefingnote.pdf

2010

Pipeline to Nowhere? Uncertainty and unanswered questions about the Enbridge Northern Gateway pipeline
http://pubs.pembina.org/reports/pipelinetonowhere-final-withcover.pdf

Duty Calls: Federal responsibility in Canada's oilsands
http://pubs.pembina.org/reports/ed-fedpolicy-report-oct2010-web-redo.pdf

Pond 1 Backgrounder
http://pubs.pembina.org/reports/pond-1-backgrounder.pdf

Canadian Aboriginal Concerns with Oilsands
http://pubs.pembina.org/reports/briefingnoteosfntoursep10.pdf

Toxic Liability: How Albertans Could End Up Paying for Oilsands Mine Reclamation
http://pubs.pembina.org/reports/toxic-liability-report.pdf

Canadian Oilsands and Greenhouse Gas Emissions: The Facts in Perspective
http://pubs.pembina.org/reports/briefingnoteosghg.pdf

Northern Lifeblood: Empowering Northern Leaders to Protect the Mackenzie River Basin from Oilsands Risks
http://pubs.pembina.org/reports/northern-lifeblood-report.pdf

How Do Two Pipelines Stack Up? Reviewing the Review Processes for the Mackenzie Gas Project and the Enbridge Northern Gateway Pipeline
http://pubs.pembina.org/reports/enbridge-mgp-comparison-june29-final.pdf

Mining vs. In Situ: What is the highest environmental impact oil?
http://pubs.pembina.org/reports/mining-vs-in-situ.pdf

Drilling Deeper: The In Situ Oilsands Report Card
http://pubs.pembina.org/reports/in-situ-report-card.pdf

Opening the Door to Oilsands Expansion: The Hidden Environmental Impacts of the Enbridge Northern Gateway Pipeline
http://pubs.pembina.org/reports/gateway-upstream-report.pdf

2009

Tailings Plan Review: An Assessment of Oilsands Company Submissions for Compliance with ERCB Directive 074
http://pubs.pembina.org/reports/tailings-plan-review-report.pdf

Climate Leadership, Economic Prosperity: Final Report on an Economic Study of Greenhouse Gas Targets and Policies for Canada
http://pubs.pembina.org/reports/climate-leadership-report-en.pdf

Pipelines and Salmon in Northern British Columbia: Potential Impacts
http://pubs.pembina.org/reports/pipelines-and-salmon-in-northern-bc-report.pdf

Carbon Copy: Preventing Oilsands Fever in Saskatchewan
http://pubs.pembina.org/reports/sask-carbon-copy-report.pdf

Highlights of Provincial Greenhouse Gas Reduction Plans
http://pubs.pembina.org/reports/highlights-of-provincial-greenhouse-gas-reduction- plans.pdf

Upgrader Alley: Oilsands Fever Strikes Edmonton
http://pubs.pembina.org/reports/Upgrader_Alley-report.pdf

Cleaning the Air on Oilsands Myths
http://pubs.pembina.org/reports/clearing-the-air-report.pdf

The Waters That Bind Us: Transboundary Implications of Oilsands Development
http://pubs.pembina.org/reports/watersthatbindus-report.pdf

The Pembina Institute's Perspective on Carbon Capture and Storage
http://pubs.pembina.org/reports/pembina-perspective-ccs-feb-19-09.pdf

Heating Up in Alberta: Climate Change, Energy Development and Water
http://pubs.pembina.org/reports/heating-up-in-alberta-report.pdf

Carbon Capture and Storage in Canada: CCS and Canada's Climate Strategy
http://pubs.pembina.org/reports/ccs-fact-sheet.pdf

2008

Danger in the Nursery: Impact on Birds on Tar Sands Oil Development in Canada's Boreal Forest
http://pubs.pembina.org/reports/borealbird-sreport.pdf

Taking the Wheel: Correcting the Course of Cumulative Environmental Management in the Athabasca Oilsands
http://pubs.pembina.org/reports/Taking_the_Wheel-report.pdf

Catching Up: Conservation and Biodiversity Offsets in Alberta's Boreal Forest
http://pubs.pembina.org/reports/CatchingUp-Offsets.pdf

Fact or Fiction: Oilsands Reclamation
http://pubs.pembina.org/reports/fact-or-fiction-report-rev-dec08.pdf

Under-Mining the Environment: The Oilsands Report Card
http://pubs.pembina.org/reports/OS-Under-mining-Final.pdf

2007

Royalty Reform Solutions: Options for Delivering a Fair Share of Oilsands Revenues to Albertans and Resource Developers
http://pubs.pembina.org/reports/Royalty_Reform_Report_May07.pdf

Haste Makes Waste: The Need for a New Oilsands Tenure Regime
http://pubs.pembina.org/reports/OS_Haste_Final.pdf

Thinking Like an Owner: Overhauling the Royalty and Tax Treatment of Alberta's Oilsands
http://pubs.pembina.org/reports/Owner_FullRpt_Web.pdf

2006

Carbon Neutral by 2020: A Leadership Opportunity in Canada's Oilsands
http://pubs.pembina.org/reports/CarbonNeutral2020_Final.pdf

Death by a Thousand Cuts: The Impacts of In Situ Oilsands Development on Alberta's Boreal Forest
http://pubs.pembina.org/reports/1000-cuts.pdf

Troubled Waters, Troubling Trends
http://pubs.pembina.org/reports/TroubledW_Full.pdf

Down to the Last Drop: The Athabasca River and Oilsands
http://pubs.pembina.org/reports/LastDrop_Mar1606c.pdf

2005

The Climate Implication of Canada's Oilsands Development
http://pubs.pembina.org/reports/oilsands-climate-implications-backgrounder.pdf

Carbon Capture and Storage: an Arrow in the Quiver or a Silver Bullet to Combat Climate Change – A Canadian Primer
http://pubs.pembina.org/reports/CCS_Primer_Final_Nov15_05.pdf

Oilsands Fever: The Environmental Implications of Canada's Oilsands Rush
http://pubs.pembina.org/reports/OilSands72.pdf

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Running out of Steam?

Oil Sands Development and Water Use in the Athabasca River-Watershed: Science and Market based Solutions

University of Toronto
Munk Centre for International Studies
at Trinity College

Environmental Research
and Studies Centre

University of Alberta

May 2007

Preamble

Alberta's oil sands (174 billion barrels)[1] are not only the world's largest capital project but now represent 60 per cent of the world's investable oil reserves.[2] But to produce one million barrels of oil a day, industry requires withdrawals of enough water from the Athabasca River to sustain a city of two million people every year.[3] Despite some recycling, the majority of this water never returns to the river and is pumped into some of the world's largest man-made dykes containing toxic waste.[4]

During the past year a variety of industry and government agencies have recognized that the intensive water requirements of unconventional oil, combined with climate change, may threaten the water security of two northern territories, 300,000 aboriginal people and Canada's largest watershed: the Mackenzie River Basin. The Petroleum Technology Alliance Canada, for example, recently stated that its "largest concern" in the oil sands was water use and reuse because "bitumen production can be much more fresh water intensive than other oil production operations."[5]

A 2006 Alberta report (Investing In Our Future) noted that "over the long term the Athabasca River may not have sufficient flows to meet the needs of all the planned mining operations and maintain adequate stream flows."[6] The report also concluded that Alberta Environment had failed "to provide timely advice and direction" on water use. The National Energy Board has questioned the sustainability of water withdrawals[7], while the Department of Fisheries and Oceans now reports that the cumulative effects of water withdrawals "could not be predicted with confidence."[8] In addition, the World Wildlife Fund predicts that warming temperatures will significantly reduce both water quality and quantity in the region.[9]

By 2015, the Canadian Association of Petroleum Producers predicts that oil sands production may total as much as three million barrels a day.[10] At that point it will be too late to address the impacts of rapid energy development on water scarcity or to responsibly consider options.

To address these critical issues, the University of Alberta's Environmental Research and Studies Centre (ERSC) and the University of Toronto's Program on Water Issues (POWI) at the Munk Centre for International Studies recently asked two prominent scholars to assess the implications of current and planned water withdrawals from the Athabasca River and options for water management.

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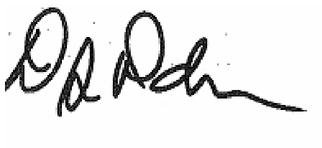
Their papers suggest that the time for critical decision-making has arrived; that energy production and the fate of water resources are inexorably linked and that innovative alternatives to business as usual are still possible.



Dr. Debra J. Davidson
Associate Professor,
Department of Rural Economy,
University of Alberta

Adèle M. Hurley
Director, Program on Water Issues
Munk Centre for International Studies
University of Toronto

Table of Contents

Section 1: Future Water Flows and Human Withdrawals in the Athabasca River

Section 2: Water Use and Alberta Oil Sands Development-- Science and Solutions: An Analysis of Options

Section 1: Future Water Flows and Human Withdrawals in the Athabasca River

by D.W. Schindler[11], W.F. Donahue and John P. Thompson

1.0 Introduction

The Athabasca River stretches from the Columbia Ice Fields near the Alberta-British Columbia border to its mouth in Lake Athabasca, at the northeastern corner of Alberta (Figure 1). Its length is estimated to be 1400 km, making it the third longest undammed river in North America, behind the Yukon and Mackenzie, and slightly longer than the Fraser. Over its length the Athabasca River drops about 800 m, with two-thirds of this drop occurring in the first 450 km.

The delta of the Athabasca River joins that of the Peace and Birch rivers to form a large (6000 km^2) complex of wetlands and lakes at the western end of Lake Athabasca known as the Peace-Athabasca Delta, one of the world's largest freshwater deltas and the largest boreal delta. The delta contains over 1000 lakes which are flooded periodically during spring ice jams of the rivers. The delta has supported large communities of aboriginal people for millennia, and is an important staging area for migratory waterfowl. Up to 400,000 birds use the Delta in spring and more than 1 million use it in autumn. It is the prime range for 5000 bison. The Delta is still largely undisturbed by humans, and has been recognized internationally as a designated RAMSAR wetland site and a UNESCO World Heritage Site.

After passing through the Delta and in some seasons the western end of Lake Athabasca, the two rivers join to form the Slave River, which flows northward, reaching Great Slave Lake near Fort Resolution. Most of the Slave River's flow is diverted westward in Great Slave Lake, flowing into the Mackenzie River, then on to the Beaufort Sea.

1.1 *Past River Flows and Time Trends in the Athabasca River*

Long-term flow monitoring records are not available for the reaches of the Athabasca River below Fort McMurray, limiting the prediction of trends in flow in the area of oil sands development or in the Athabasca Delta. A short period of record was collected at Embarras, from 1971-1984. The Athabasca's average flow at Fort McMurray during April to November of 1954-2002 was 859 cms (cubic meters per second; Figure 2). Median flows were considerably lower, 177 cms, during December-March when the river is covered with ice and snow and runoff is reduced by cold weather. The reach below Fort McMurray is about 295 km in length but only drops by 11.5 m.

[11]. Thanks to Brad Stelfox (Forem Technologies), Preston McEachern (Alberta Environment), Suzanne Bayley (University of Alberta), and Lyle Lockhart for figures 5, 11, 18, and 20 respectively, and to Beverly Levis and Margaret Foxcroft (University of Alberta) for help with the manuscript. We would like to acknowledge the Munk Centre for their financial support.

The highest flow recorded during the above period was 4700 cms on July 15, 1971. The lowest recorded flow was 75 cms on December 2, 2001 (Figure 2). During 2001, following a succession of dry years, flows were less than 100 cms for almost 4 months in winter. Flows have been well below average for most years since 1980. This is of concern, because current EUB regulations will require future oil sands plants to store water off river for only 30 days of operation, capturing the water at high flow conditions. As we shall discuss below, projections based on the combination of climate warming and increasing water withdrawals indicate that winter flows less than 100 cms will occur with increasing frequency in the future.

Climate warming, drought, human withdrawals and modifications to catchments in the prairie provinces are well known to be causing changes in the annual and seasonal flows of rivers and the levels and water quality of lakes and rivers. In the past century, river flows and lake levels have declined throughout the prairie provinces (Gan 2000; Schindler and Donahue 2006, Sauchyn et al. 2006, Schindler et al. 2004). Summer (May-Aug) flows in the Athabasca River at Fort McMurray had declined by 29% between 1970 and 2005 (Figure 3). The decline in summer flow has been less than that of any other river originating on the eastern slopes of the Rocky Mountains in Canada (Schindler and Donahue 2006), probably because relatively little water is withdrawn from the Athabasca River above Fort McMurray. The river has no dams or reservoirs that disturb seasonal flow patterns and compared to other major rivers there is relatively little development in the catchment upstream of Fort McMurray.

Oilsands mining already accounts for the largest consumption of water in the Athabasca River basin. Licences issued for withdrawals of surface water for all purposes allow up to 535,930 dam^3 (cubic decametres or 1000 cubic metres) to be used (consumed or lost). This represents 8% of all licenced surface water use in Alberta. Oil sands mines accounted for 76% of licenced water use in the Athabasca River basin in 2005 with another 8% for other petroleum purposes, including steam assisted gravity drainage (SAGD) and injection. (Figure 4; Golder Associates 2004). Most other licensed uses draw water from reaches of the river above Fort McMurray (Figure 6).

Until very recently, only two oil sands plants have been withdrawing water from the Athabasca River. These two plants, Suncor and Syncrude, produce less than 400,000 barrels per day of oil. In recent years, new oil sands plants by Albian Sands, CNRL, Shell, Fort Hills have begun operating or been approved, and current licensed bitumen production is about 1 million barrels per day, requiring water withdrawals at a maximum rate of 7.5 cms in 2010, dropping to 6.6 cms by 2013 (Figure 7).

As of 2005, 21 licences surface water have been issued for oilsands mining in the Athabasca River basin. These licences allow withdrawals of up to 453,051 dam^3 and account for 61 per cent of total surface water allocations in the entire Athabasca basin. These allocations are for six major oilsands projects (Table 1).

Table 1. Allocated and licensed water use for the six approved and operating oil sands projects (AMEC 2007).

Licensee	Allocation (dam^3)	Licenced Use (dam^3)	Return Flow (dam^3)
Albian Sands Energy Inc.	58,930	58,930	0
Canadian Natural Resources Limited (Horizon)	114,020	114,020	0
Fort Hills Energy Corporation	46,117	46,117	0
Shell Canada Limited (Jackpine)	72,400	72,400	0
Suncor Energy Inc.	68,550	29,895	38,655
Syncrude Canada Ltd	93,034	93,034	0
Total	**453,051**	**414,396**	**38,655**

Of these allocations, 82% is for water from the mainstem of the Athabasca River (341,657 dam^3) and 13% is water from major tributaries, including the Tar, Muskeg and Steepbank rivers and Beaver and McLean creeks (52,615 dam^3). The balance of licenced water use (5% or 20,124 dam^3) is for the collection and use of surface run-off. Some oilsands plants also have licences that allow them to withdraw and use up to 93,040 dam^3 of groundwater. Only one oilsands operation has return flow requirements in its licence. In total, existing licences allow up to 414,396 of surface water to be used, either through consumption or losses. This represents 77 per cent of licenced water use in the entire basin, and represents a maximum diversion of 12.5 cms from the Athabasca River and its tributaries.

Only three of the major oilsands projects were operating in 2005, including Suncor, Syncrude and Albian Sands. These three projects are allowed to withdraw up to 191,375 dam^3 from the Athabasca River, 9,015 dam^3 from tributaries, 8,932 dam^3 from groundwater, and 20,124 dam^3 from surface water run-off. For 2005, these three operations reported withdrawing about 98,900 dam^3 of water from the Athabasca River, equivalent to an average of 3.1 cms. This represents about 52 per cent of the water that these projects are allowed to withdraw. There is no information on withdrawals from other sources, such as surface run-off and groundwater, or on any amounts of water that may have been returned to the river after use.

In a recent 2007 decision, the Alberta Energy and Utilities Board (EUB) approved an application by Imperial Oil for the Kearl Oil Sands Project, despite that total water extractions for existing and already approved oilsands projects already exceed the maximum withdrawal permitted under the Phase 1 Water Management Framework, described below (Section 14.1.1, EUB 2007). The new project has requested a water license for 80 million m^3/y (2.5 cms) initially, increasing to 104 million m^3/y (average 3.3 cms) at the project's peak. Maximum withdrawal rates from the river by the Kearl project are expected to be 4.9 cms, and comprise 2.3% of historical average annual flows in the Athabasca River at Ft. McMurray (EUB 2007).

Various organizations have predicted future water requirements for bitumen extraction and these forecasts are quite different. Here we use recent preliminary forecasts prepared by AMEC. Figure 7 shows the maximum rates of water extraction by oil sands mines, measured in cubic metres per second (cms). The figure includes water use by the three existing operations, the three additional major projects (Jackpine, Horizon, Fort Hills), and the Imperial Oil/Exxon Kearl mine.. The forecasts show that maximum rates of extraction are expected to increase to 13.9 cms by 2010 and then decline to about 13.0 cms in 2015. As was the case in 2005, actual water use is expected to be less than the maximum allowed in the licences, with volumes depending on natural run-off, annual bitumen production, and changes in operating efficiency.

Two other oil sands mines are expected to start using water in 2010 and 2011, but their use is not shown in Figure 7. These include the Deer Creek (Total E&P Canada) Joslyn North Mine Project and the Synenco Energy/SinoCanada Petroleum Northern Lights Mining and Extraction Project. However, their water requirements are relatively small and would likely increase withdrawals by about seven per cent, reaching nearly 13.9 cms by 2015. These projections do not include the water requirements of any other future oilsands mines.

In the future, total bitumen production in the oil sands is expected to supply most of Canada's oil production of 5 million barrels per day by 2020 (Stringham 2007). About one third of this would be by thermal recovery, including steam assisted gravity drainage (SAGD). Allocations of surface water for thermal oil recovery allow withdrawals of up to 38,212 dam^3, of which 35,394 dam^3 can be used and the remainder (2,817 dam^3) is to be returned. Water licences issued for thermal recovery account for seven per cent of all surface water use in the Athabasca River Basin. Detailed estimates of water used for thermal purposes have been prepared by GEOWA based on EUB data and suggest that about 8,108 dam^3 of surface water was diverted for thermal purposes in 2005. This suggests that licensees were only using 23 per cent of their entitlements.

According to recent forecasts from the EUB and CAPP, the general trend in Alberta is for *in situ* bitumen production to increase as fields are developed. The EUB forecasts that *in situ* crude bitumen production (thermal) will increase from 69,700 m^3 per day in 2005 to 170,000 m^3 per day by 2015. CAPP forecasts that *in situ* crude oil production (thermal) will increase to 277,433 m^3 per day by 2015, and then decrease to 274,094 m^3 per day by 2020. Thermal production in the Athabasca/Peace basin is expected to follow the overall Alberta trend because the province's most important oilsands deposits, the Athabasca Wabiskaw-McMurray (AWM), are located within the basin. The forecast of future water use for thermal recovery in the Athabasca River Basin (Figure 8) assumes that the amount of water required for thermal activities will follow the trend in bitumen production: water use will increase significantly to 2015 and then decline slightly. Average withdrawals for thermal bitumen extraction from 2015 onward would average from1 to1.6 cms.

In summary, the total water used for oil sands mining and thermal extraction in the Athabasca River basin is expected to be 15-15.6 cms by about 2015.

1.2 *Instream Flow Needs (IFN)*

It is generally recognized that to keep the geometry, fisheries and water quality of rivers in a normal, productive condition, it is necessary to maintain a minimum amount of water in the river, referred to as the instream flow needs or IFN. Modern methods for estimating IFN recognize that different species have different habitat requirements at different seasons. They require high-intensity data sets and usually three-dimensional modelling procedures (reviewed by Richter et al. 1997). It is generally recognized that a flow regime to protect an aquatic ecosystem must account for a wide range of natural flow variation and consider multiple components of the aquatic ecosystem (Richter et al. 1997; Annear et al. 2004; Golder Associates

2004; Anderson et al. 2006). Recently, an IFN for the South Saskatchewan River based on multiple criteria concluded that the river required 85% of normal flow (Clipperton et al. 2003). IFNs have not been agreed upon for other rivers of the prairie provinces. IFN considerations are important for the ecological integrity of the Athabasca River, which contains 31 species of fish, several of which are important for subsistence in aboriginal communities. Some species of importance spawn in the spring, during high flow conditions, and others spawn in late fall, with larval development occurring over several months under winter ice. Therefore, IFN considerations will vary for different fish species, as well as for maintaining the various fluvial and riparian dynamics that are critical to a river's sustenance. The long period under ice and snow and the sensitivity of the Athabasca Delta to small differences in river levels may make the Athabasca River more sensitive than most rivers for which IFN have been estimated.

IFN also apply to navigation. During the summer months, the only surface transportation possible between Fort Chipewyan and Fort McMurray is by boat, using the Athabasca River. Residents are already complaining that low river levels in the past several years have made it difficult to use the river for transportation. Future changes in channel morphology and river flow will affect the possibility for transportation, especially for barges and other large watercraft. These too must be addressed by an IFN plan.

For the Athabasca River, in 2003, the Cumulative Environmental Management Association (CEMA) was directed by the Alberta Energy and Utilities Board in the 2003 CNRL and Shell hearings to recommend an IFN by December 2005. Alberta Environment and the Federal Department of Fisheries and Oceans (DFO) were directed by EUB to estimate the IFN if CEMA failed to do so by the required date. CEMA did not have an IFN prepared by December 2005 because a draft report prepared for CEMA by Golder Associates (2004) was not approved by CEMA's membership. Alberta Environment and DFO prepared draft IFNs during 2006 (AENV/DFO 2007). Their report recommended interim guidelines for IFN, termed the Phase 1 Water Management Framework, based on three very general flow-specific management zones: green, yellow and red, representing ample, borderline and low flow conditions, respectively (Figure 9). In brief, in the green zone, when flows are above approximately 140 cms (Termed HDA80), it is assumed that flows are sufficient for both ecosystem and human needs and that up to 15% of the river's flow can be taken for human and industrial needs. In the yellow zone (100-140 cms, the zone between HDA80 and Q95,), it is recognized that low flows may cause stress to aquatic ecosystems, requiring that water withdrawals for human use must be reduced. In the red zone (<100 cms, or Q95), the system is assumed to be under acute stress, equivalent to a 1 in 20 year drought during past conditions. Long-term ecological sustainability may be affected.

A Phase 2 Management Framework, based on specific ecological criteria, is to be in place by late 2010 (AENV/DFO 2007). AENV/DFO (2007) do not consider the effects of predicted climate warming on flows of the Athabasca River in the Phase 1 Management Framework, and it is not explicitly recognized in Phase 2. Also, it is noteworthy that current and approved withdrawals would already put the river in "red" zone conditions for several months in winter during low flow years (Figure 10). Indeed, "red zone" conditions would occur in some years with no human withdrawals at all. Such low flow conditions are likely to occur more frequently as climate warms in the 21st century, and withdrawals for oil sands and other human uses increase. As a result, the amount of water available to industry would decline. As we discuss below, the

Athabasca system shows evidence of being unusually sensitive to very high and very low flow conditions. The lack of consideration of climate change and high flow conditions in the currently-used Phase 1 Management Framework make it ineffective at protecting IFN in the Athabasca River.

On March 27-28, 2007, Alberta Sustainable Resource Development assembled the Instream Flow Needs Technical Task Group Expert Workshop to consider the data available and future needs to make a good estimate of IFN for the Athabasca River. It was generally recognized that the current data base is inadequate for the task. Among data identified as needed were more detailed analysis of dissolved oxygen in the river and its tributaries, more precise estimates of the relationship between river stage and flow rates under ice and in river reaches below Fort McMurray, and data that will permit identification of relationships between river flow and particular ecological processes. These include spawning success, recruitment, and sustainability of fisheries; frequency, duration, and degree of flooding in the Delta region; and fluvial dynamics involved in channel formation, scouring, and movement of riverbed sediments. Special emphasis was recommended on assessments of side channels and perched basins in the Athabasca Delta that flood periodically, providing spawning and nursery habitat for fish.

1.2.1 Winter: The most vulnerable period for the biota of the Athabasca River?

Because of the long period sealed under ice and snow, the Athabasca River is susceptible to low oxygen as a result of respiration and decomposition of organic matter in the water as it flows slowly toward the Athabasca Delta. This factor was of concern to the Alberta-Pacific Review Panel seventeen years ago (Alberta Pacific Environmental Impact Assessment Review Board 1990) and was studied in more detail during the Northern River Basins Study in the 1990s. A considerable oxygen sag was observed, and modelled with acceptable accuracy for the reach of the Athabasca River above the Grand Rapids (Chambers et al. 1995). Oxygen in the reach from Fort McMurray to the Athabasca Delta was not studied by the NRBS. The reach is slow flowing and largely covered with ice and snow, therefore low oxygen is of concern at low winter flow. Alberta Environment has compiled some data for lower reaches of the river and its tributaries. Values less than provincial water quality guidelines of 8.5 mg/L for early life stages and 6.5 mg/L for adults have been recorded at several locations, particularly near the mouths of tributaries (Figure 11). Data for the Muskeg River show the lowest oxygen at the lowest flows recorded under winter ice in early 2001, suggesting that declining flows will cause declining oxygen. Low oxygen concentrations under ice are known to be detrimental to the eggs and fry of fall-spawning species such as lake whitefish and bull trout. Other concerns are that late fall-early winter river stages may be too low for fall-spawning fish to reach spawning sites, or to allow fry to occupy key nursery sites in the river during winter.

In addition to the above-noted downward trend in summer flow, there has been an analogous downward long-term trend in lowest winter flows (Figure 12). Using predictions from several global climate models, Bruce (2006) projected a decrease in runoff from the Athabasca River basin below Fort McMurray of about 30% by the mid-21st century. He further noted that winter low flows had been less than 110 cms in 10 of the past 24 winters, and that more frequent low flows are projected for the future. Gan and Kerkhoven (2004) use a number of climate models to project that winter low flows would be 7 to 10 % lower in the next four decades. However, these reductions are far less than the projection from the long-term trend determined by linear regression from winter low flow measurements since 1970. These suggest that the decline in flow may be greater, with an average decrease in lowest winter flow of 1.5 cms per year (Figure 12). It is noteworthy that this trend line is projected from a period (1970-2002) of modest climate warming, when only two oil sands plants were in operation, and there were few other withdrawals of significance from the Athabasca River. With several more oil sands plants approved and planned, and the high potential for accelerated future climate warming, it is clear that under the Management Framework, there will be insufficient water for future oil sands development.

1.2.2 High flows may also be very important to the integrity of the river ecosystem

The above-mentioned IFN panel identified several factors of possible importance to IFN that relate to maximum flows. Firstly, highest flows are generally those that shape the morphometry of river channels (Leopold et al. 1964). In other ecosystems and in the Peace-Athabasca Delta, the damping of high flows has destroyed fish habitat (Ko and Day 2004; Valdez et al. 2001, Dalton 2003; Environment Canada 2005) and deltaic habitats (Zwarts et al. 2006; Peters et al. 2006). Secondly, high flows generally flood the shallow side channels and mouths of tributaries where spring spawning occurs in the Athabasca, and which are critical nursery habitats for young fish and other organisms. At present, there are not data that link river stage to the availability of spawning and nursery habitat, the recruitment of fish stocks, or the maintenance of deltaic wetland ecosystems. In the Athabasca River, perched basins in the delta area and side channels do not flood every year even without human water withdrawals or climate warming. In some important spawning and nursery areas, access can be allowed or denied by a few centimetres change in river stage (for example, Richardson Lake, a critical spawning and rearing habitat for walleye, depends on a few centimetres of water to maintain connectivity to the main river system. A recent study of 57 basins in the Peace-Athabasca Delta has shown that there is a wide range of flooding frequency, from every year to very seldom (Wolfe et al. 2007). In other river systems, it has become necessary to allow periodic floods to occur to regenerate fish stocks, fish habitats, or other riparian and deltaic features (Ko and Day 2004; Zwarts et al. 2006). Thus, the assumption of the Phase 1 Water Management Framework that high flow conditions do not affect fisheries or fish habitat are probably invalid, and more detailed field study is needed to verify whether the 15% removal indicated in the Phase 1 Management Framework can affect critical spawning and migration habitats.

It is noteworthy that in addition to withdrawals for extraction of bitumen, many of the oil sands companies are expecting to withdraw water from the river to fill End Pit Lakes, created at the end of mining operations and proposed as replacement fish habitat for tributaries damaged by mining operations. Griffiths et al. (2006) have calculated that in 2041, withdrawals from the river for filling end pit lakes will require 302.7 million m^3 of water, or an average of 9.6 cms. It is not stated whether these projections include expected evaporation losses from the end pit lakes, and it is not clear whether the needs to fill end pit lakes are included in existing water allocations.

1.2.3 Longitudinal time trends in runoff from the Athabasca River catchment

Rivers of the prairie provinces drain catchments that are sub-humid to semi-arid, except for the upper reaches in the Rocky Mountains and foothills. Typical runoff from low elevation parts of the catchments in the mid 20th century was from less than 50 to about 150 mm per year. We examined the water yields and recent trends for different reaches of the Athabasca River, using data from the gauging stations shown in Figure 13. While the flows at the most upstream station, Sunwapta, have increased due to accelerated glacial melt, the catchment runoff water yields to the Athabasca decline as one proceeds downstream (Figure 14). It is also noteworthy that there have been downward trends with time for runoff in all subcatchments below Hinton. In this lower 93.7% of the Athabasca River watershed, catchment water yield has declined by about 50% in the past 30 years (Figure 14).

1.3 *Past and Projected Changes in Climate of the Prairies and the Oil Sands Area*

Previously, we presented climate trends and projections for the prairies (Schindler and Donahue (2006). Most sites have already undergone a 2-3 ˚C increase in temperature, mostly since 1970. We also noted coincidental widespread large decreases in snowpacks at most locations on the prairies. Future projections for the prairies indicate increases in temperature of about 6 ˚C may occur by the end of the 21st century, if average climate model projections are realized (Figure 15).

Fort McMurray has already undergone an increase of more than 2 ˚C between 1945 and 2005 (Figure 16), and Fort Chipewyan has increased by more than 3 ˚C. Looking ahead, Ft. Chipewyan is projected to undergo a further 4.8 ˚C increase, with coincidental increases in precipitation of 32 mm. However, potential evapotranspiration is projected to be substantially higher than any projected increases in precipitation, as a result of warmer temperatures and longer summers. While potential evapotranspiration requires that moisture deficit does not inhibit evapotranspiration, land surfaces are wet throughout the summer in much of the Athabasca Basin below Fort McMurray, where lakes and wetlands are abundant. Also, lake evaporation and evapotranspiration were found to be equal in other northern studies (Newbury and Beaty 1980). Almost all sites in the prairie provinces have had declining winter periods with snow on the ground, and a trend toward shallower maximum snowpacks (Schindler and Donahue 2006).

We have used a climate-based model of streamflow, verified with historical data (1919-1998; $r^2 = 0.73$), to predict changes in water yield of several catchments of 278-30,800 km^2 in the Athabasca Lowlands of northeastern Alberta into the 21st century. The model predicts significant declines in total April-October streamflow for the entire range in catchment areas. With an average warming of 3 ˚C (projected for about 2050) average projected declines in streamflow were 8-26% for the various catchments, with maximum declines of 17-71% in the warmest and driest years. With an average warming of 6 ˚C (projected for about 2100, if carbon emissions remain near "business as usual"), projected streamflows declined by averages of 24-68, with declines of 52-100% in the warmest, driest years (Figure 17). These results suggest the kinds of risks to water supply that may accompany predicted warming and the associated increases in evapotranspirative water losses.

1.4 *Modifications to the Catchment of the Lower Athabasca River*

Much of the oilsands area is overlain by wetlands, especially wooded fens. In lay terms, this is several meters of peat, with spruce or larch trees of 10 m or so in height growing from the surface (Figure 18). The fen areas are crossed by many small streams that are tributary to the Athabasca River. This wetland complex serves an important hydrological function, absorbing snowmelt and large runoff events, and allowing the water to trickle slowly into the Athabasca River throughout the year. In this regard, the peatland/tributary complex serves much the same function as a capacitor in an electrical circuit. For example, development of the CNRL Horizon mine alone is expected to reduce discharge of groundwater into the Athabasca River by up to 30,000 m^3/day (Bruce 2006). If this estimate is correct, it would represent another 0.35 cms decline in average stream flow.

These vast areas of these peatlands and many kilometres of stream channels, such as the Muskeg River, are destroyed or drainage rerouted by oil sands mines in order to reach bitumen-containing layers. At present, there has been little reclamation attempted in most of the oilsands area, and no reclamation has been certified by Alberta Environment (Figure 19). The area has been visited and studied by several internationally-renowned wetland scientists, and it is generally agreed that the area cannot be reclaimed to its original condition, and it is unlikely to be restored to any condition with equivalent hydrological function. The possible effects of these modifications on river flows have not been considered by AENV/DFO (2007), and judging from the CNRL estimate above, the cumulative effect could be quite serious.

1.5 *Water Use by the Oil Sands: A Collision Course with River Flows*

The projected 15 to 15.6 cms for oil sands production in the Athabasca Basin represents 8.5 to 9 per cent of current median low flows, and 20 to 21 per cent of the lowest winter flows recorded to date. If climate continues to warm, runoff continues to decline and winter low flows continue to decrease as suggested in Figures 12 and 17, the water needs of the oil sands could reach a critical proportion of winter low flow. Similarly, if the lower Athabasca River is affected by climate warming as projected for nine of its lowland tributaries, substantial declines in river flow may be expected between April and October as well. Recent discussions on an Industry Water Sharing Agreement suggest that unused allocations will be distributed to new and future oilsands producers (EUB 2007). However, given the high proportion of allocations that is used (Table 1), there appears to be little opportunity for expansion given the likely water availability. The Phase 1 Management Framework provides some limitations on water use, but may be too generous in some seasons, based on our analysis.

1.6 *Water Flows and Water Quality Considerations*

The occasional low oxygen concentrations observed under winter ice near the mouths of tributaries to the Athabasca River were mentioned earlier. At present, it is not known whether oxygen depletion is aggravated by low winter flow conditions, and this knowledge will be necessary in order to predict the effects of climate warming and increased withdrawals on biota.

Similarly, the entire Athabasca River below Ft. McMurray contains sediments with high polycyclic aromatic hydrocarbon (PAH) concentrations. In many cases, concentrations were in excess of Interim Sediment Quality Guidelines (Canadian Council of Ministers of the Environment 1999; Evans et al. 2002). In addition, undisturbed tributaries to the Athabasca River contain sediments with particularly high concentrations of PAHs compared to the mainstream river (Headley et al. 2001). Concentrations of PAHs at some sites were sufficient to cause low survival of fishes and invertebrates in sediment toxicity studies (Evans et al. 2002). In an early study, Barton and Wallace (1979) showed that benthic invertebrate communities in the lower Athabasca River were less diverse than those upstream of the oil sands. However, because PAH concentrations were similar both above and below the oil sands, investigators concluded that the values were likely the natural result of seeps from geological deposits of oil sands (Evans et al. 2002). It is unknown whether recent increases in oilsands mining and activity have resulted in any changes in PAH loading since this mid-1990s study.

EROD (for ethoxyresorufin-*O*-deethylase) activity is a well established *in vivo* indicator of exposure to PAHs, dioxins, and similar chemicals. It is regarded as a highly sensitive indicator of contaminant uptake in fish, and it has been associated with embryonic deformity and mortality, and other biological effects. High EROD activities in fish were found in the oil sands region of the Athabasca River during the Northern River Basins study. Values below Fort McMurray were several times higher than those on the upstream reaches of the Athabasca River, despite the presence of organic pollutants known to induce EROD at some upstream sites (**Figure 20**). In this reach of the river, the most likely stressors that affect EROD are PAHs, including several known carcinogens. At present, baseline data on the concentrations and toxicity of these mixtures of pollutants are inadequate to develop adequate water quality guidelines and objectives.

The high levels of disturbance in wetlands and tributary reaches will expose large new deposits of oil sands and reroute groundwater flows, which could potentially increase exposure of fishes and other organisms to PAHs and other toxic compounds. Unfortunately, it is not known if concentrations are related to flow volumes.

1.7 *Special Concern for the Peace-Athabasca Delta*

The integrity of the Delta is very sensitive to water level, with perched shallow lakes and side channels of the river systems depending on a range of flooding conditions. Some lakes are flooded almost every year, and others seldom. The largest group of lakes are intermediate between these two extremes, providing a diversity of successional stages and habitat characteristics that support the high diversity of wildlife in the area. Typically the Delta floods in the spring, when ice jams block the Peace and/or Athabasca rivers, causing water to flood the area, rejuvenating lakes and wetland areas. Historically, the generation of major spring flood events has been triggered by large snowmelt events in tributaries in the mid- to lower-portions of the Peace and Athabasca basins (Prowse et al. 2006). Flooding of the Delta has already been compromised by climate-induced declines in spring snowmelt, and by the damping of spring flows on the Peace by Bennett Dam (Prowse et al. 2006). This has caused extensive losses of perched lakes, along with the muskrats, fish and waterfowl that supported the aboriginal communities (Green 1992). Projections are for continued reductions in the frequency of ice-jam flood, primarily because of reduced snowpack (Prowse et al. 2006). Consequently, even small changes in water level at high flow could further reduce the frequency, duration, and extent of flooding of the Delta, contributing even further to losses of ecological integrity (Environment Canada 2005). Development in the Peace Basin and its tributaries is also a concern, with potential for reducing water quantity and compromising water quality (NRBS 1996)

1.8 *Concern for the Slave River and Delta*

Flows in the Slave River have also declined considerably in the 20th century (Figure 21) reflecting changes to the Peace and Athabasca rivers, which supply most of the water. The Slave River Delta in Great Slave Lake is also dependent on spring flows and ice jams to rejuvenate lakes and river channels. It affords subsistence to several hundred aboriginal people in the Fort Resolution and Fort Fitzgerald area, and spawning habitat for fishes in Great Slave Lake. The decline has been blamed by many local residents on water removal by the oil sands. However, at present, climate warming and reductions in peak flows on the Peace River caused by the operation of Bennett Dam still appear to be the primary reasons for the decline (Prowse et al. 2006).

1.9 *Summary*

- Average summer and winter low flows of the Athabasca River have declined for over 30 years as a result of climate warming and decreased snow. Runoff has decreased by 50% in the 93.7% of the Athabasca Basin that is downstream of the Rocky Mountains. Flows have also declined in the Peace and Slave Rivers.

- Models based on forecast climate warming for the 21st century predict a further decrease in snowpacks, runoff, and river flow.

- The recently propose Phase 1 Water Management Framework is inadequate to protect the Athabasca River system. It does not ensure flooding of side channels and delta lakes that are critical spawning and nursery habitats for fish and other organisms at high flow. Its reliance on past conditions offers little protection for the ecosystem from low oxygen, high contaminant concentrations or reduced winter habitat under winter ice. It also offers no measures for protection of the large Delta wetland ecosystem and its great diversity of plants and animals. It does not account for the effects of climate warming.

- At present, data on instream flow needs are insufficient to allow construction of a plan that would protect the river system.

- Projected bitumen extraction in the oil sands will require too much water to sustain the river and Athabasca Delta, especially with the effects of predicted climate warming. Water levels in Lake Athabasca and flows in the Slave River will likely continue to decrease.

- To protect water resources and fisheries, and sustain aboriginal lifestyles in the lower Athabasca River and downstream, measures must be taken to reduce consumptive water use, and gain knowledge necessary to produce an effective, protective, science-based water management plan.

1.10 *Figures*

Figure 1. A map of the lower reaches of the Athabasca River.

Figure 2. Seasonal flows in the Athabasca River from 1957-2002. From Alberta Environment submission to EUB hearing, CNRL Horizon Project, 2003.

Figure 3. The decline in average summer flow in the Athabasca River.

Figure 4. Licensed water use from the Athabasca River by sector. Source AMEC.

Figure 5. Trends in bitumen extraction and water needs for oil sands operations. Figure by Brad Stelfox.

Figure 6. Distribution and type of licensed water withdrawals from the Athabasca River in 2005. From AMEC.

Figure 7. Projected maximum water diversions by major oil sands mines, Athabasca River Basin. Prepared by AMEC.

Figure 8. Projected future surface water use for thermal extraction, Athabasca River Basin. Prepared for Alberta Environment by AMEC.

Figure 9. A depiction of the weekly flow exceedance curves and the three management zones proposed in Management Phase 1, AENV/DFO 2007.

Figure 10. Per cent withdrawal from the Athabasca River by the oil sands at median winter low flow under historical conditions. From Alberta Environment presentation to EUB Hearing on CNRL Horizon Project, 2003.

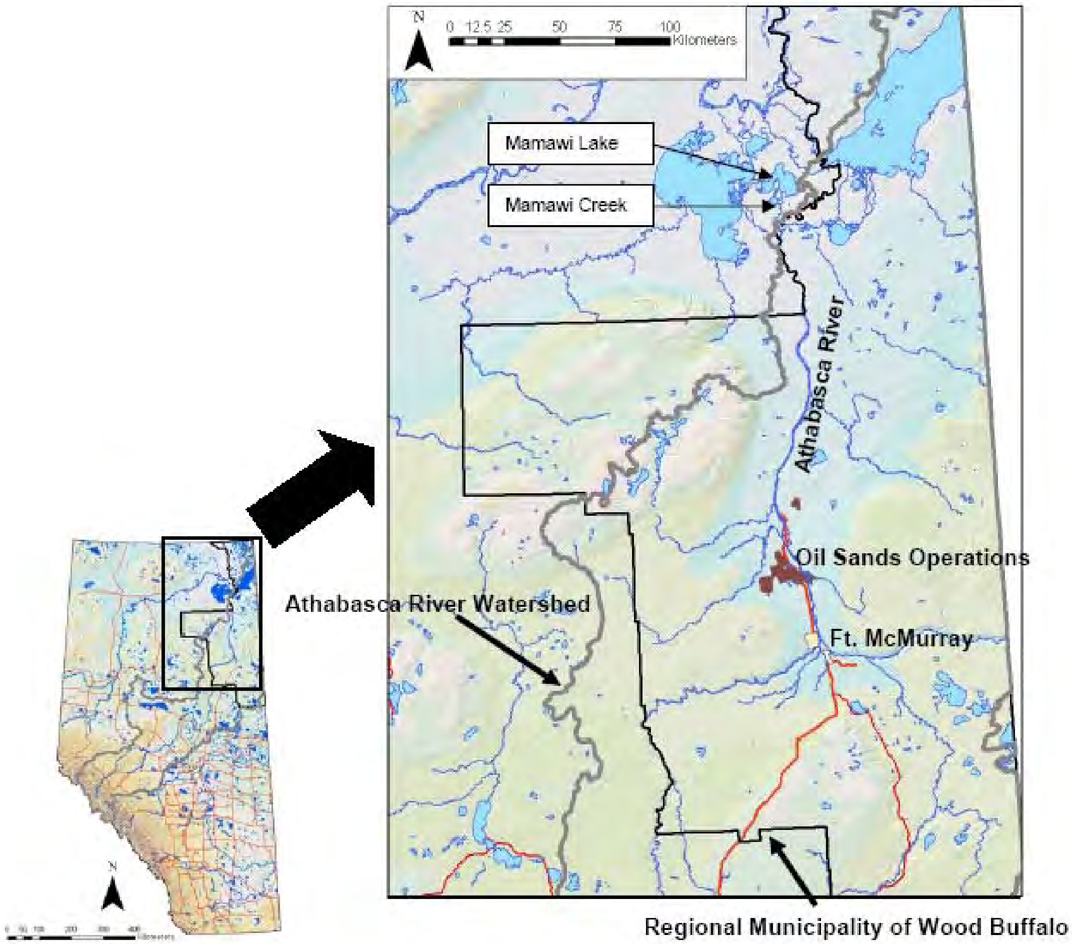
Figure 11. Dissolved oxygen concentrations (mg/L) as measured with datasonde in winter at several stations on the Muskeg River, a tributary of the Athabasca River below Fort McMurray. The period shown is 1998-2001, with lowest values in December 2000 and January 2001. WSC is the Water Survey of Canada gauging site 6 km from the river's mouth. AWQG are the Alberta Water Quality Guidelines, shown as horizontal red bars. Mouth = Muskeg River 50-100 m upstream of its confluence with Jackpine Creek. Jackpine is at the confluence of Jackpine Creek with the Muskeg River. M u/s J is on the Muskeg just upstream of Jackpine Creek. Symbols preceded by Act are values, but measured by the chemical Winkler method. Source: Alberta Environment

Figure 12. The trend over time in lowest winter flows in the Athabasca River. The dotted line is the regression through measured data points.

Figure 13. The location of gauging stations on the Athabasca River (stars).

Figure 14. The change in average water yields from Athabasca River subcatchments over the period 1971-2001. The bars are the beginning and endpoint of the regression lines through all data points.

Figure 15. Projected changes in average annual temperature for the prairie provinces. From Schindler and Donahue (2006).



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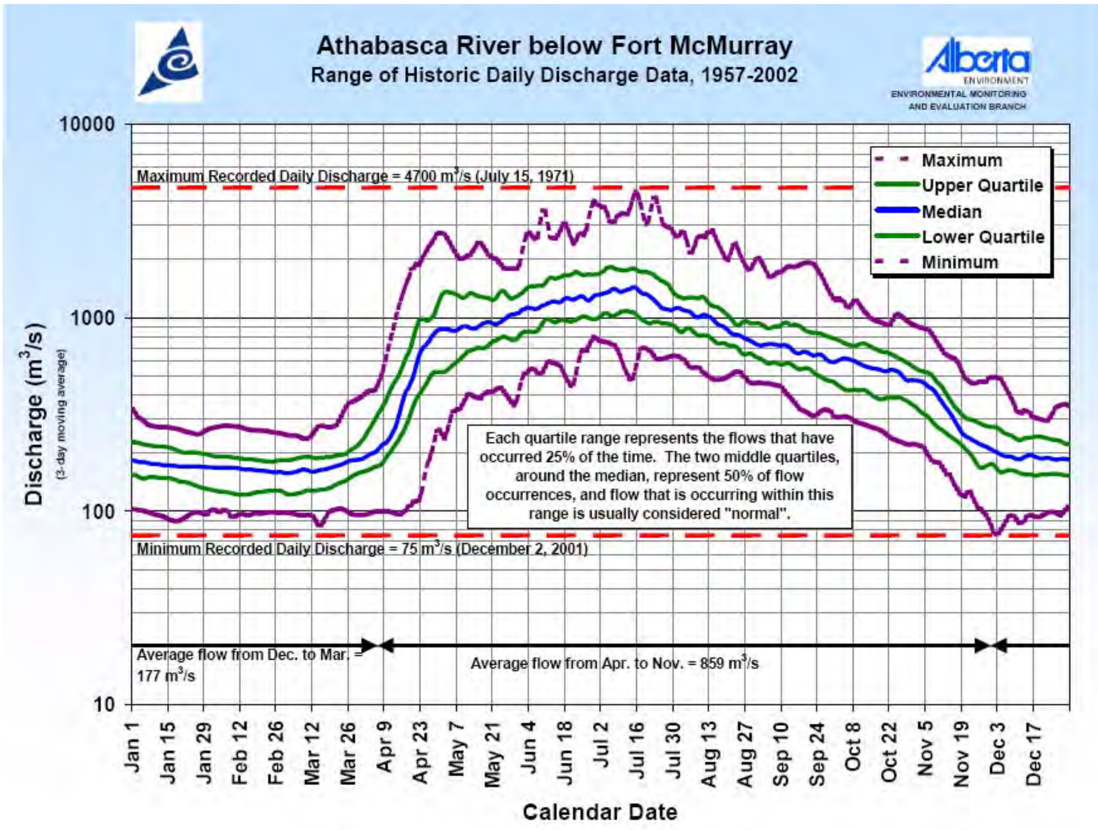


Figure 2. Seasonal flows in the Athabasca River from 1957-2002. From Alberta Environment submission to EUB hearing, CNRL Horizon Project, 2003.

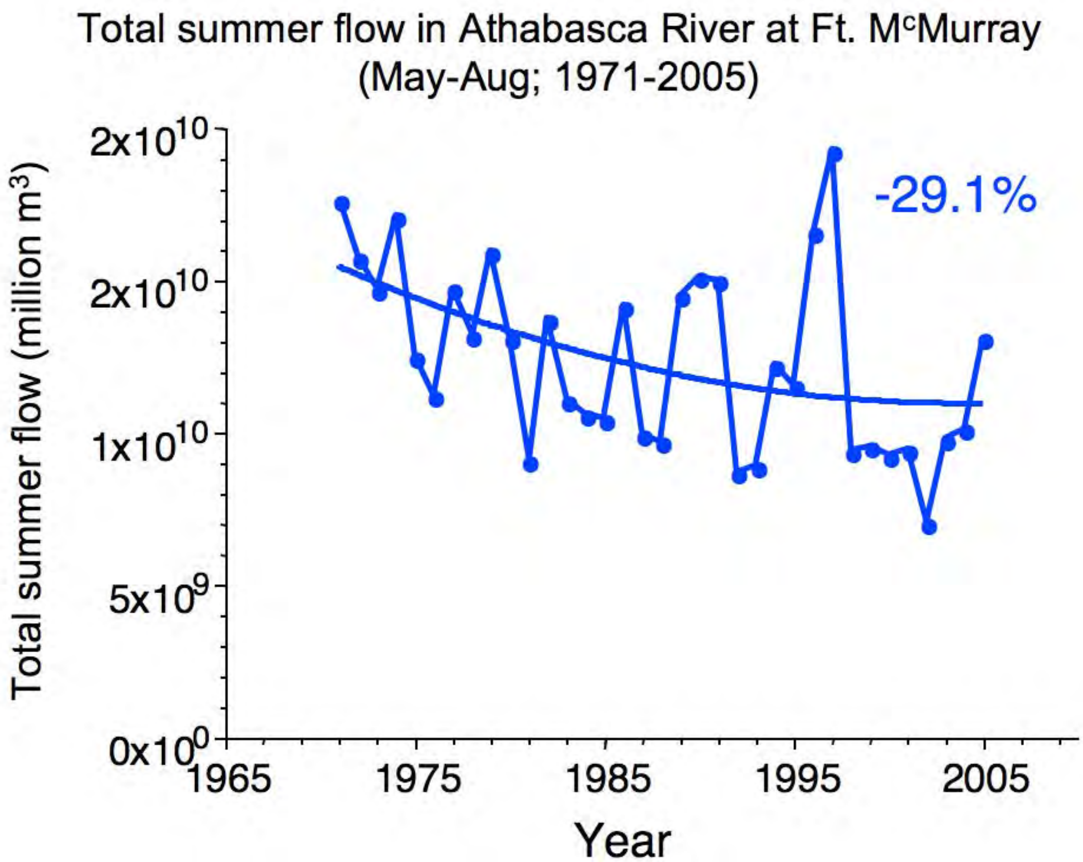


Figure 3. The decline in average summer flow in the Athabasca River.

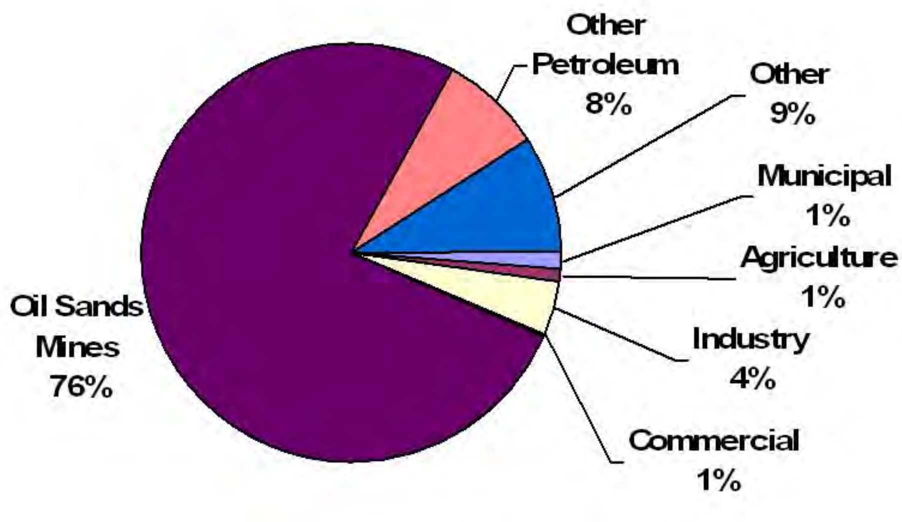


Figure 4. Licensed water use from the Athabasca River by sector. Source AMEC.

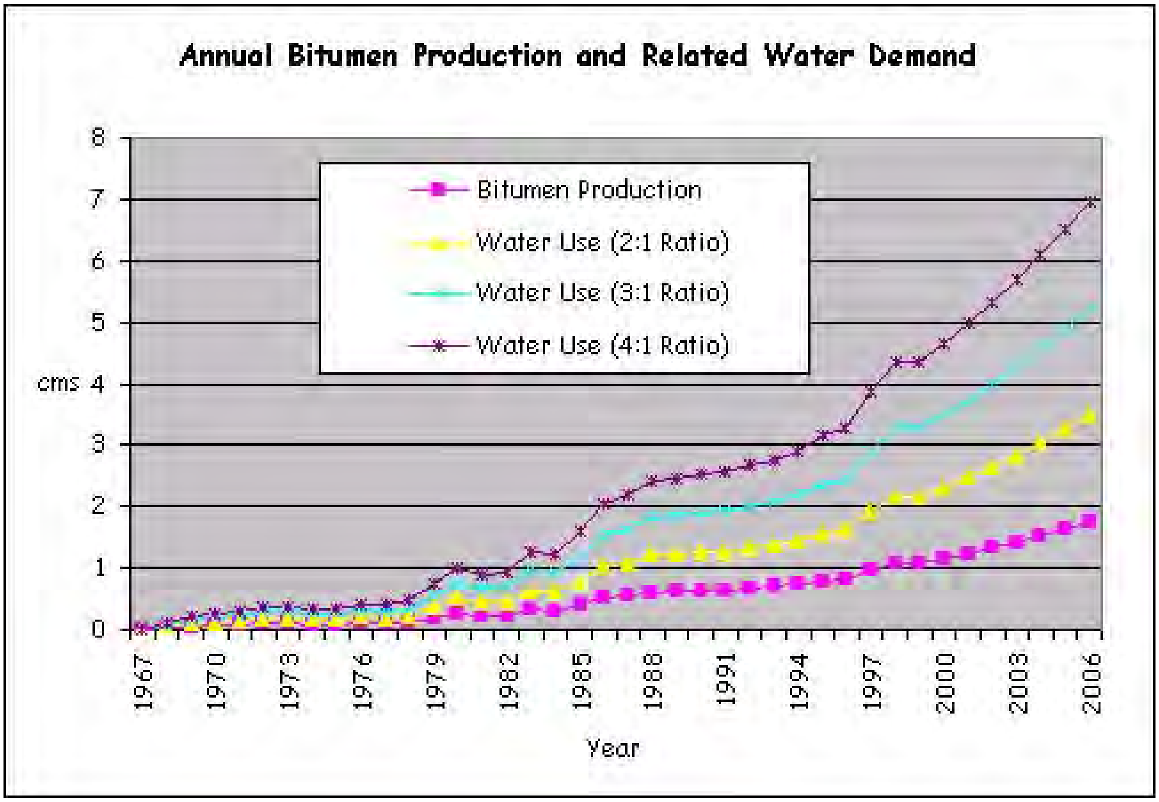


Figure 5. Trends in bitumen extraction and water needs for oil sands operations. Figure by Brad Stelfox.

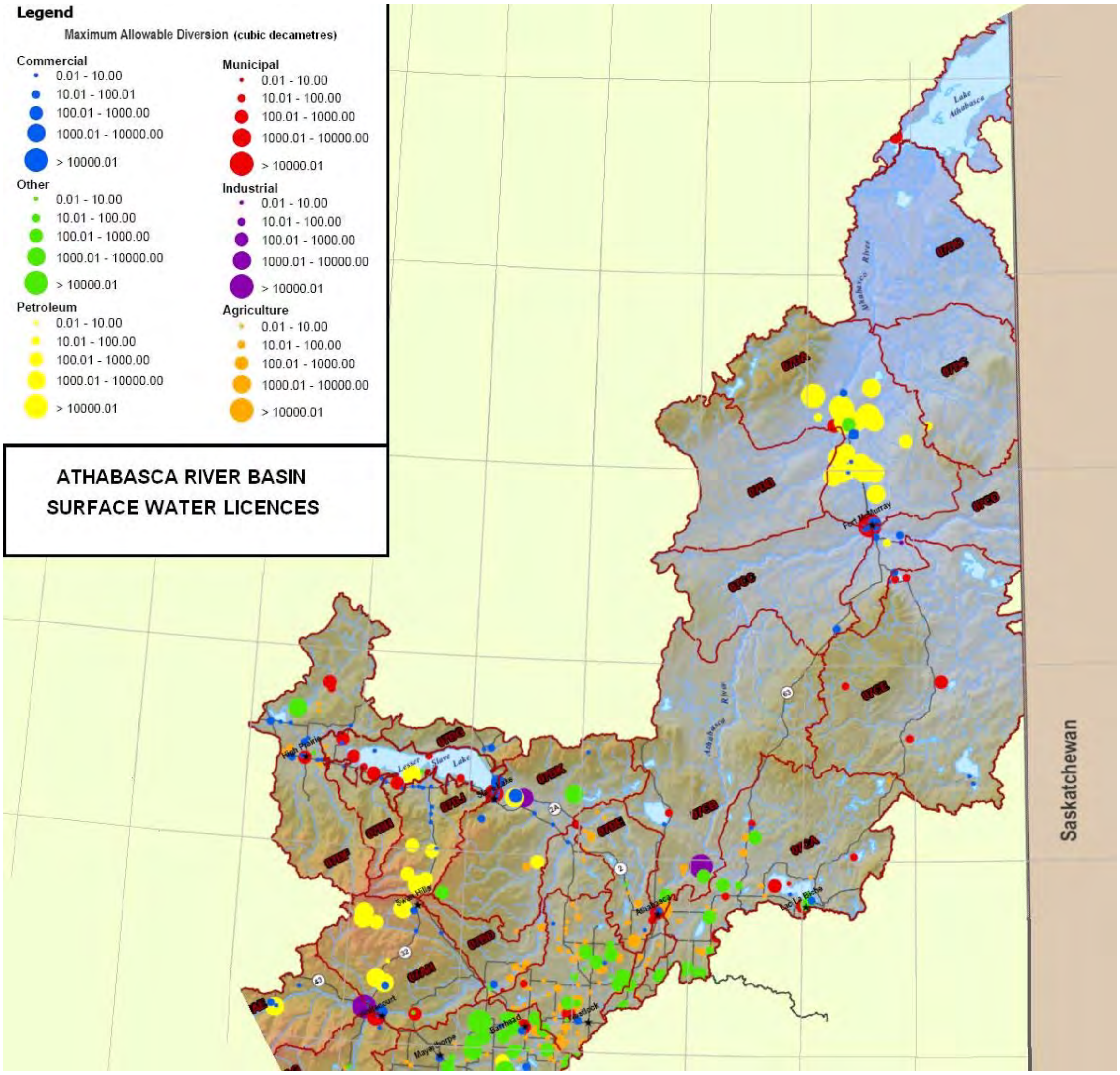


Figure 6. Distribution and type of licensed water withdrawals from the Athabasca River in 2005. From AMEC.

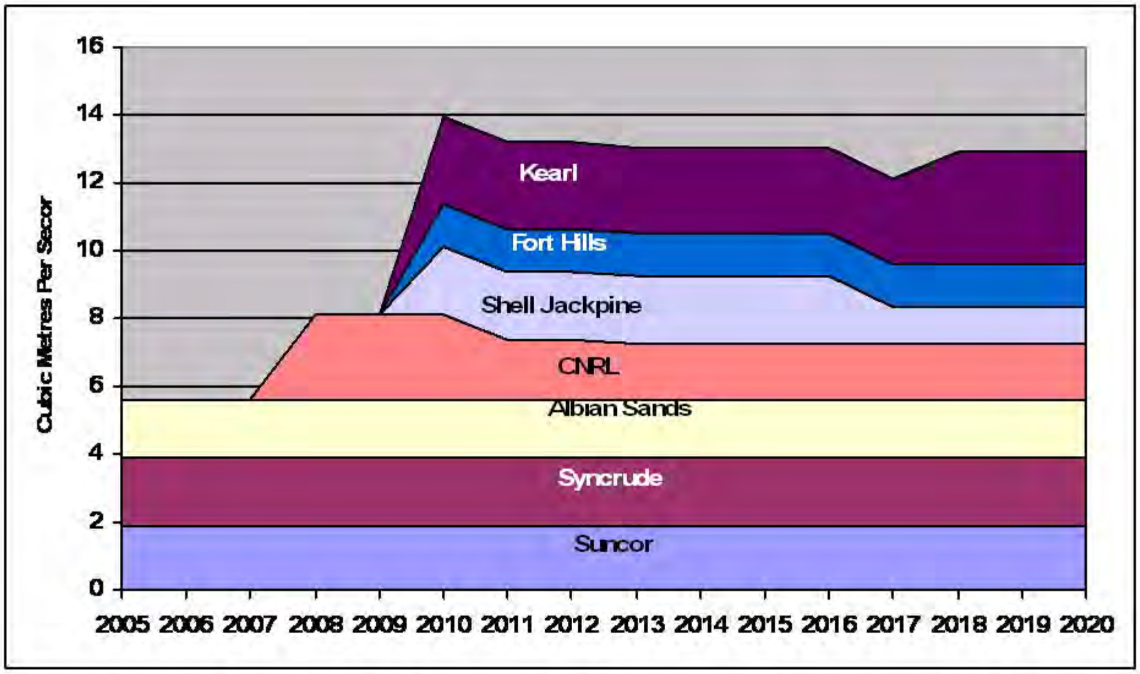


Figure 7. Projected maximum water diversions by major oil sands mines, Athabasca River Basin. Prepared by AMEC.

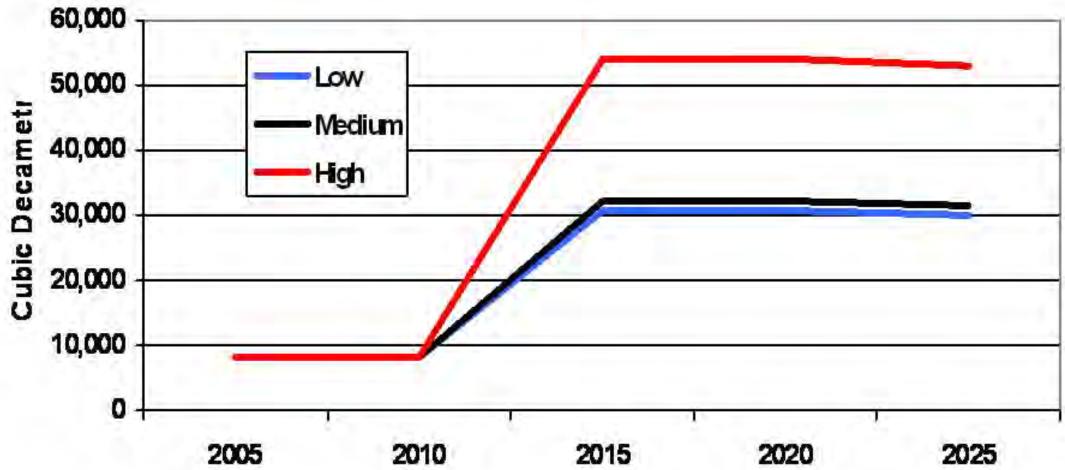
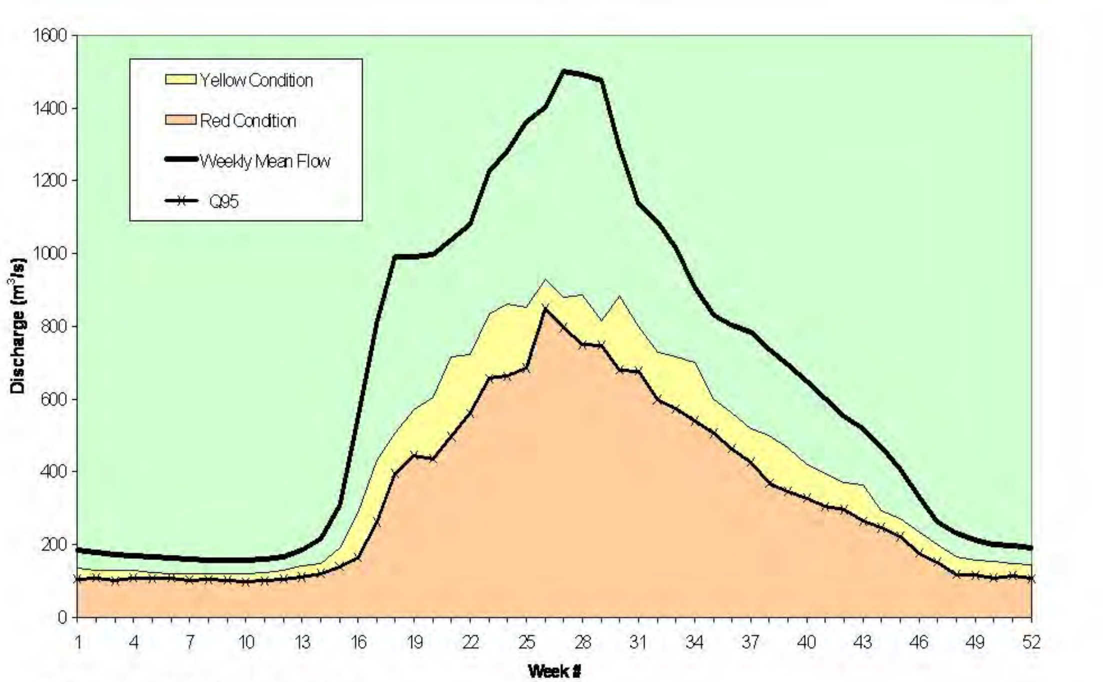


Figure 8. Projected future surface water use for thermal extraction, Athabasca River Basin. Prepared for Alberta Environment by AMEC.



Source: DFO/AENV 2007

Figure 9. A depiction of the weekly flow exceedance curves and the three management zones proposed in Management Phase 1, AENV/DFO 2007.

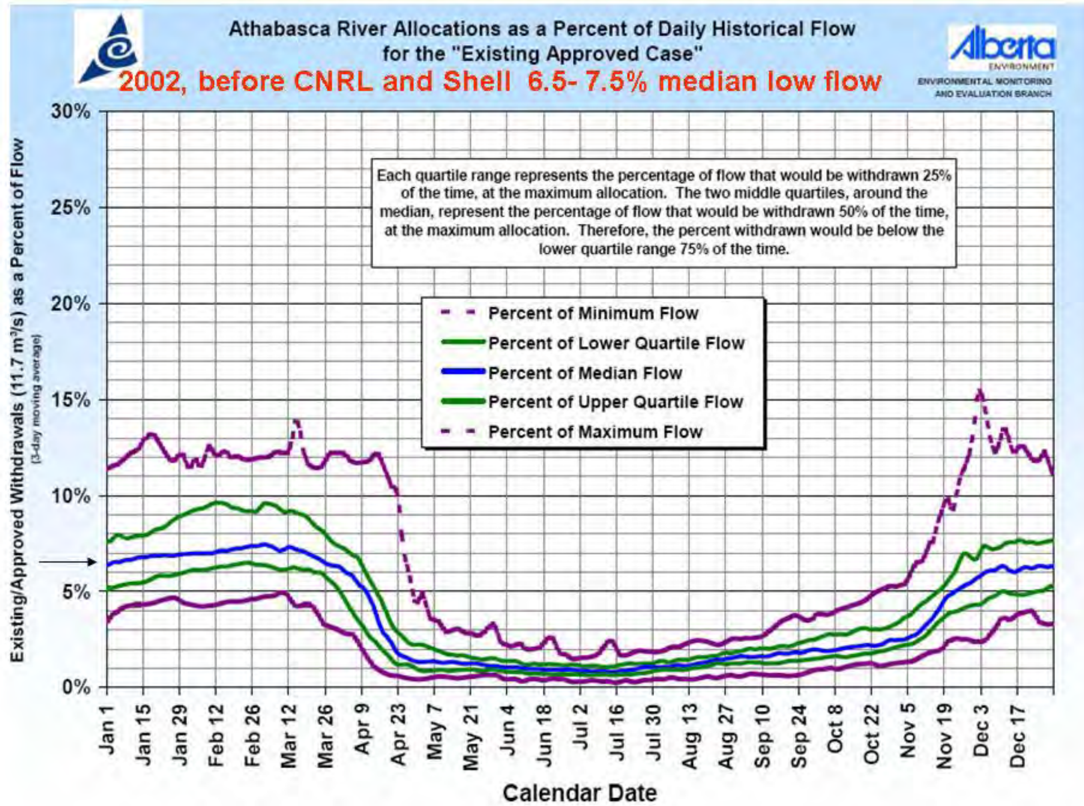


Figure 10. Percent withdrawal from the Athabasca River by the oil sands at median winter low flow under historical conditions. From Alberta Environment presentation to EUB Hearing on CNRL Horizon Project, 2003.

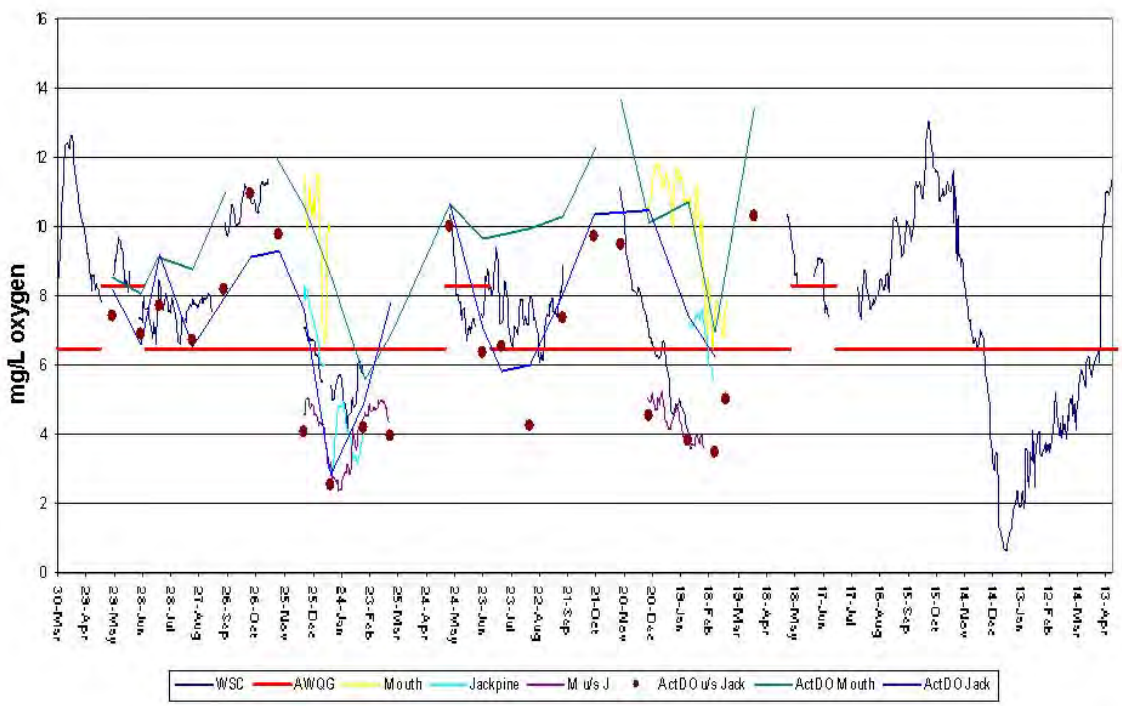


Figure 11. Dissolved oxygen concentrations (mg/L) as measured with datasonde in winter at several stations on the Muskeg River, a tributary below Fort McMurray. The period shown is 1998-2001, with lowest values in December 2000 and January 2001. WSC is the Water Survey of Canada gauging site 6 km from the river's mouth. AWQG are the Alberta Water Quality Guidelines, shown as horizontal red bars. Mouth = Muskeg River 50-100 m upstream of its confluence with Jackpine Creek. Jackpine is at the confluence of Jackpine Creek with the Muskeg River. M u/s J is on the Muskeg just upstream of Jackpine Creek. Symbols preceded by Act are values, but measured by the chemical Winkler method. Source: Alberta Environment.

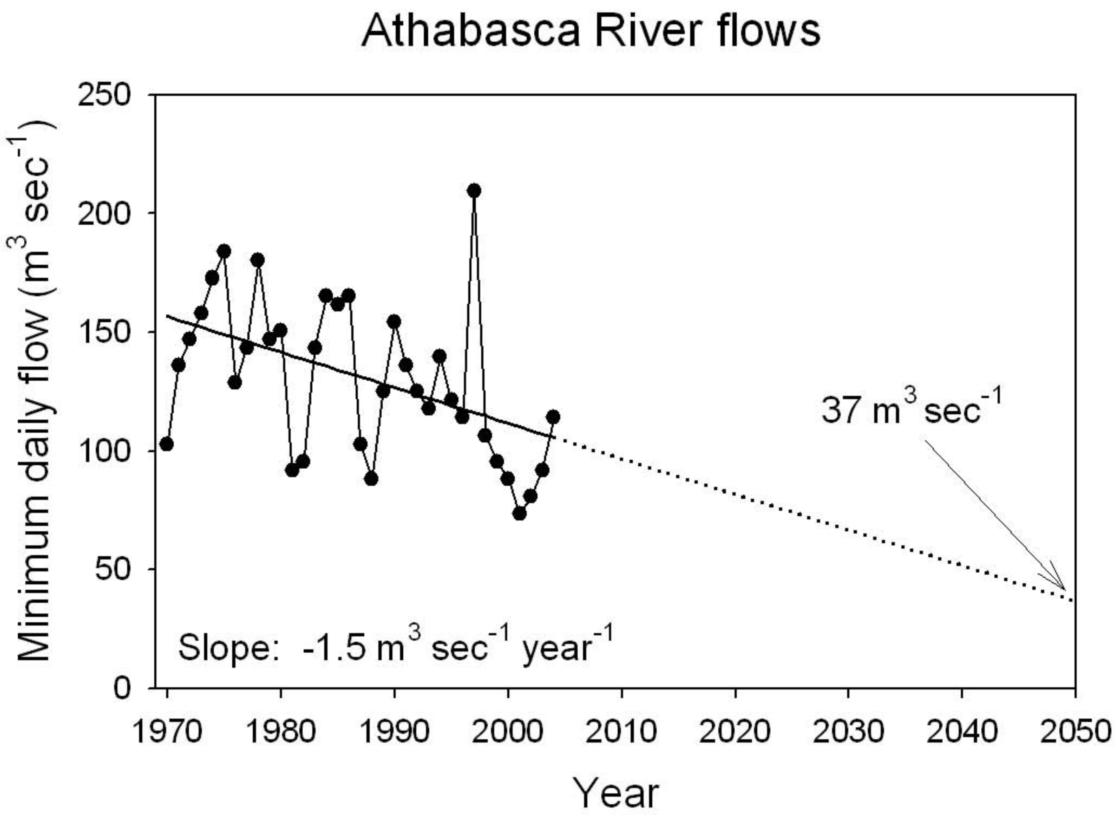


Figure 12. The trend over time in lowest winter flows in the Athabasca River. The dotted line is the regression through measured data points.

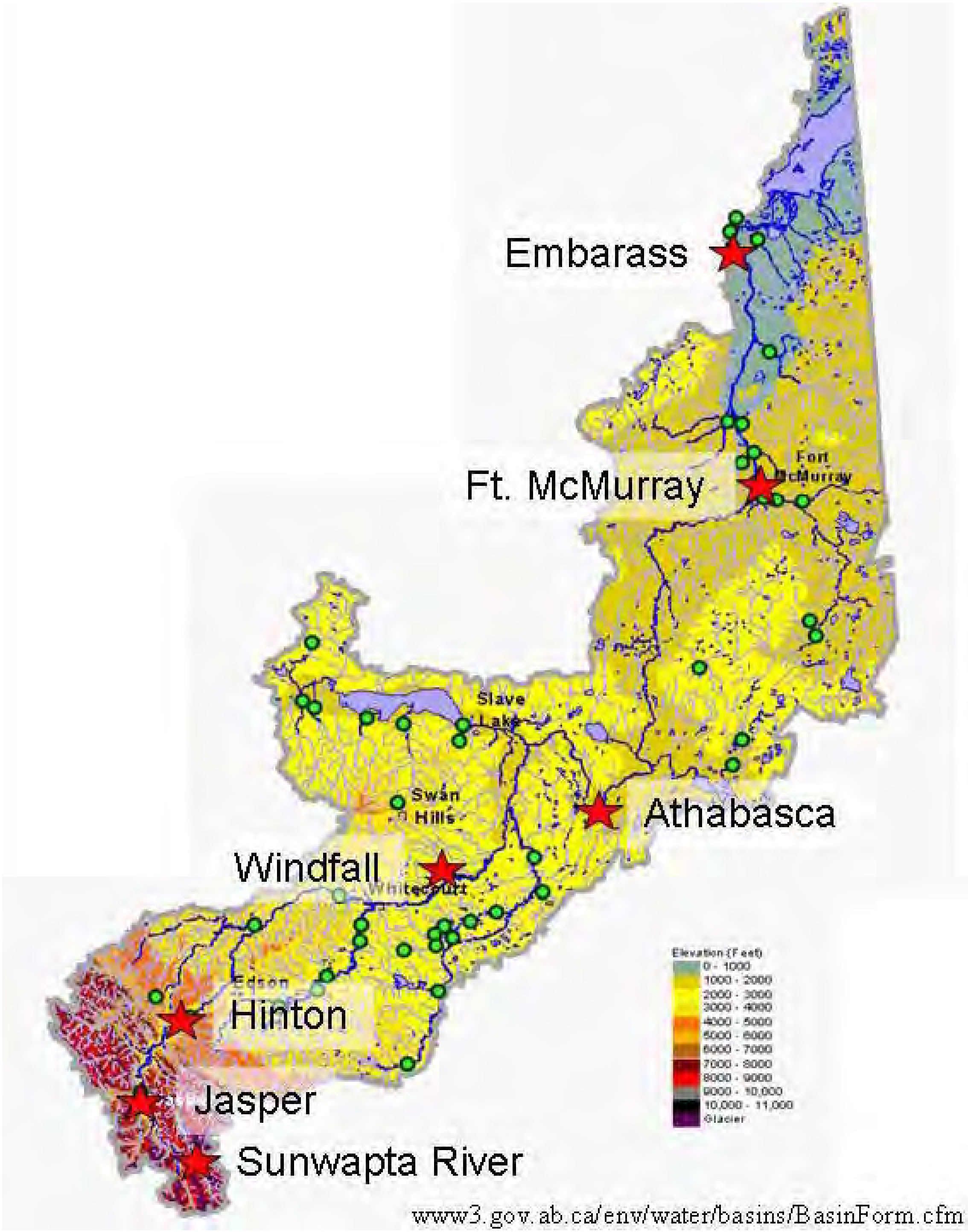


Figure 13. The location of gauging stations on the Athabasca River (stars).

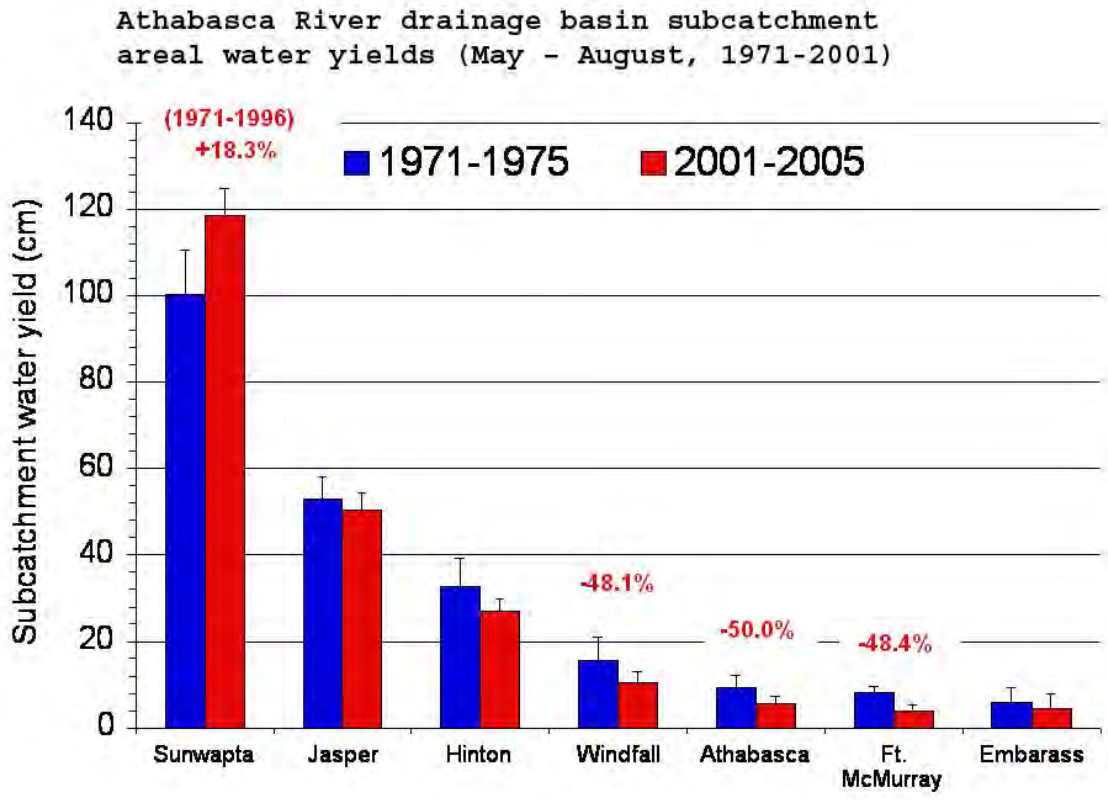


Figure 14. The change in average water yields from Athabasca River subcatchments over the period 1971-2001. The bars are the beginning and endpoint of the regression lines through all data points.

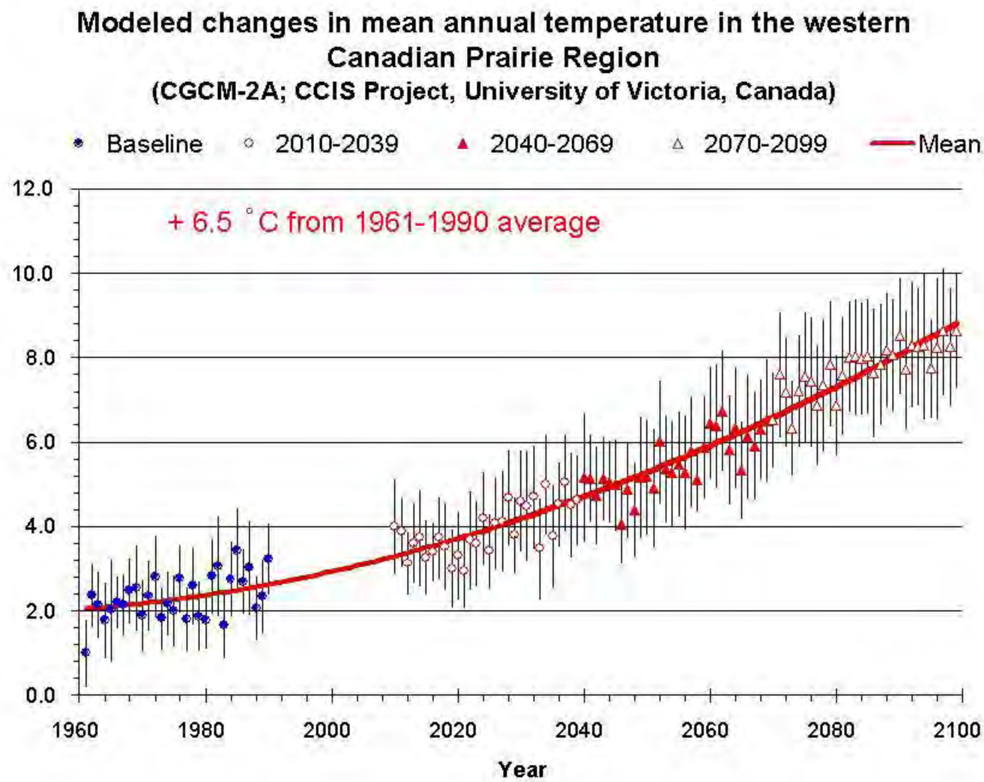


Figure 15. Projected changes in average annual temperature for the prairie provinces. From Schindler and Donahue (2006).

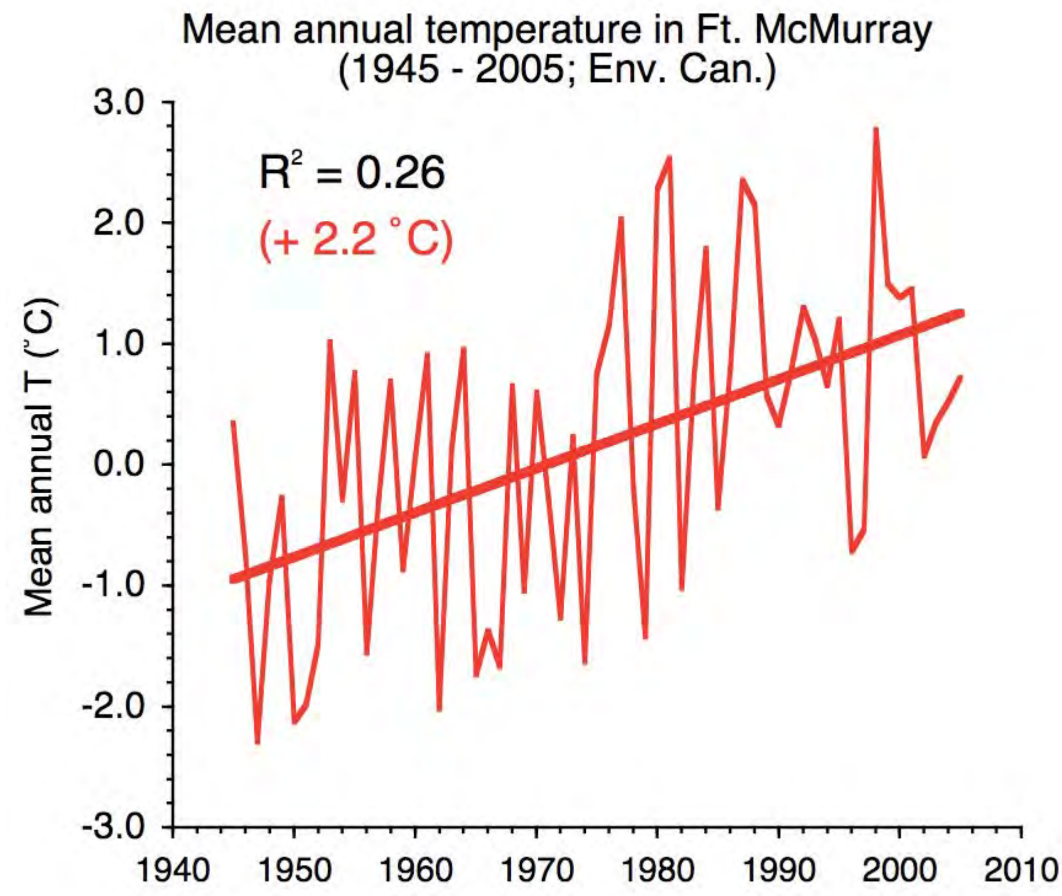


Figure 16. Trends in average annual temperature for Fort McMurray 1945-2005.

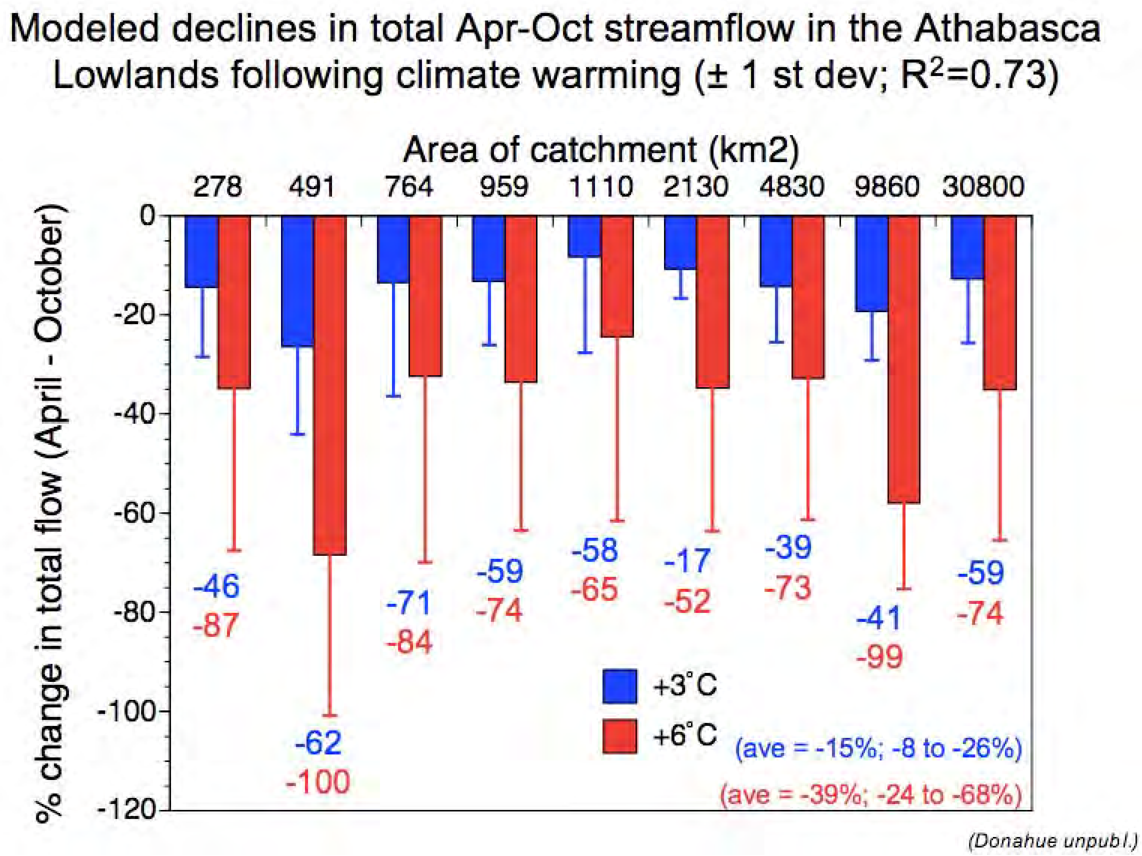


Figure 17. Modeled predictions of changes in runoff from several catchments in the Athabasca lowlands as the result of climate warming as the result of 3 degree (blue) and 6 degree (red) increases in average temperature.

Figure 18. A wooded fen, typical of 50-65% of the area mined by the oil sands. Photo by Dr. Suzanne Bayley.

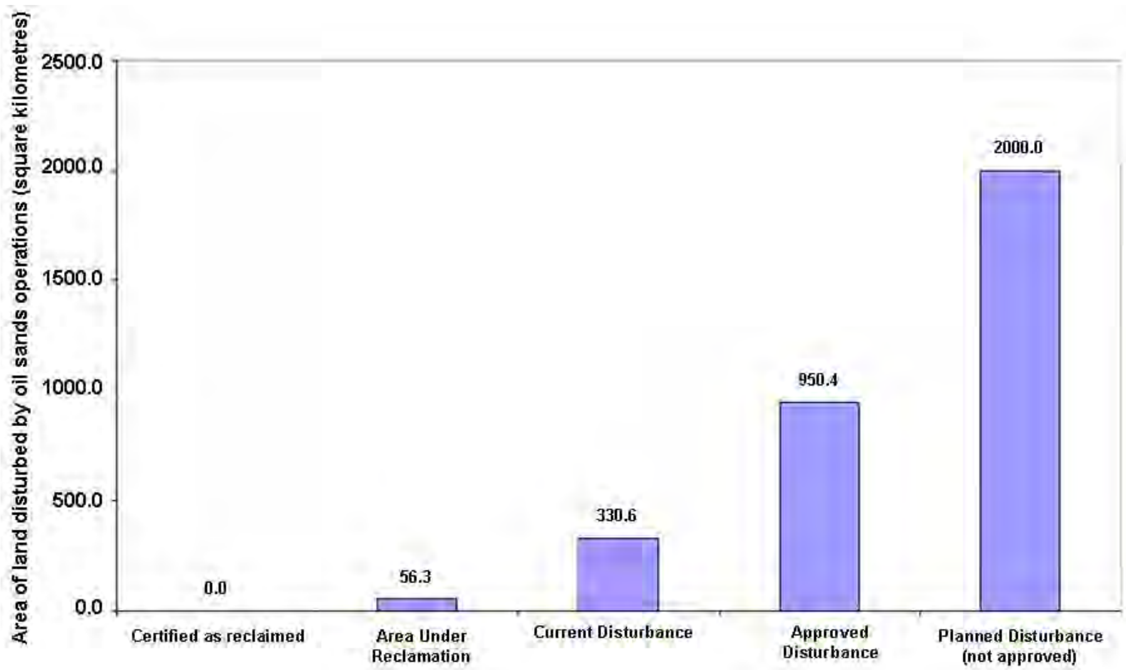


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Figure 19. A summary of reclamation in the oil sands area, 2004. Source: Alberta Environment.

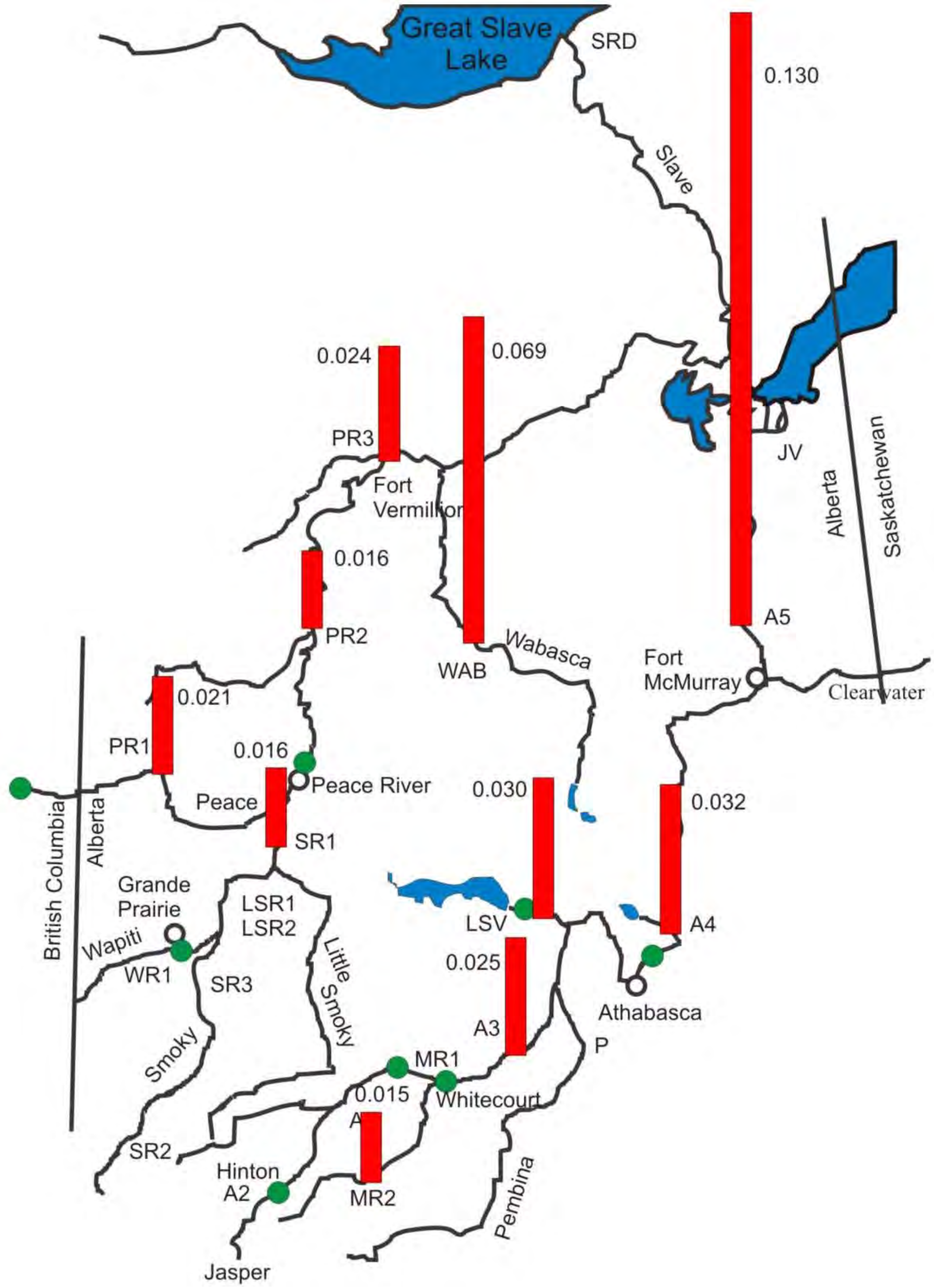

Figure 20. Relative EROD activities in immature burbot taken during the Northern River Basins study. Figure from Dr. Lyle Lockhart.

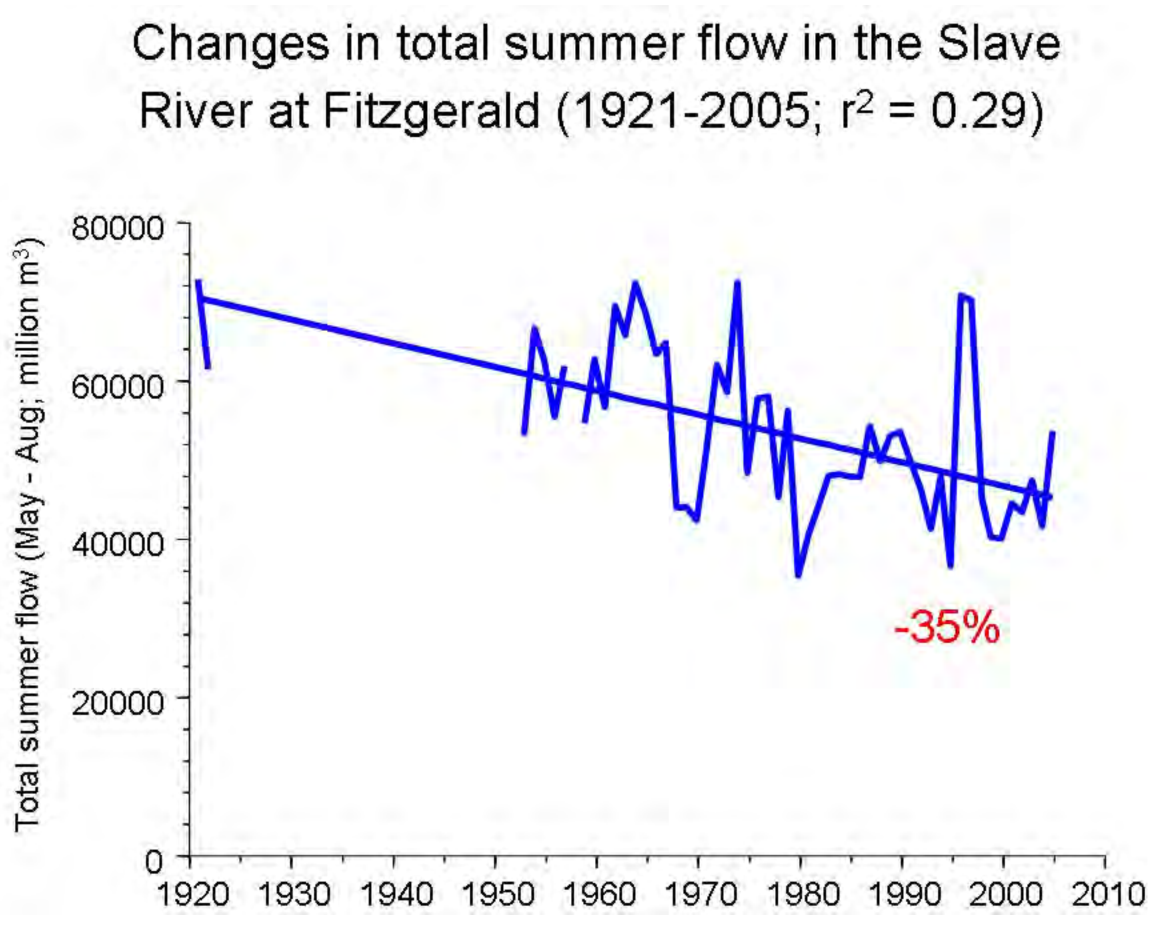

Figure 21. Summer flows in the Slave River at Ft. Fitzgerald, showing a 35 percent decline over the period of record (1921-2002). Note the large gap in records in the early part of the figure.

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Section 2: Water Use and Alberta Oil Sands Development-- Science and Solutions: An Analysis of Options

by Vic Adamowicz[12]

2.0 Introduction

The section above shows that economic activity, as well as ecological function and community well being will be limited by the availability of water in the Athabasca basin. Planned increases in economic activity may not be feasible, or may be more costly than originally thought, given water scarcity concerns. This section of the paper describes economic considerations in the allocation of water resources with a focus on balancing environmental, social and economic objectives. In particular, a set of policy options or "mechanisms" are presented in which environmental goals may be achieved more cost effectively. This discussion is intended to be consistent with Alberta's Water for Life Strategy (2003) in that it attempts to use science, information and novel policy tools to balance objectives in water resource allocation.

2.1 *Alberta's Current Framework*

Prior to the implementation of the *Water Act* (1999), Alberta employed the mechanism of administrative apportionment in which rights to water quantities are provided by the government. This "first in time, first in right" system provides older or senior licences priority in times of scarcity. Technically, demands from the oldest licences are to be met first with remaining water allocated based on an ordering implied by the date of licence. Unlike other jurisdictions (e.g., Australia) the licences are not based on a share of a determined flow but are defined by quantities of water. This approach to allocating water has been criticized for numerous reasons (Horbulyk 2007). While tying water rights to the land provided the security needed to encourage land settlement, this reduced the flexibility to move water to higher valued uses. The mechanism tends to result in water being used in lower value uses; if new higher value uses arise they are given a lower priority licence. Inability to trade water rights adds to the inflexibility of the system.

The new Alberta *Water Act* (1999) included several revisions that can help improve the allocation of water resources (see, e.g. Horbulyk 2007; CAPP 2002). In particular, the new *Act* included a framework for water rights trading to improve water resource allocation. The *Act* also included changes regarding term licences (licences with fixed end dates but with the option for renewal), and promoted the development of water management plans to facilitate improved conservation of water resources in regions of the province. Since the passing of the *Water Act* there has been some (albeit limited) activity in transferring permanent water rights (Horbulyk

[12] Thanks to Mark Anielski (Anielski Management Inc), Don Dewees (University of Toronto), Chokri Dridi (University of Alberta), John Thompson (AMEC Earth and Environmental) and Terry Veeman (University of Alberta) for their review comments on this paper. Also thanks to Marian Weber (Alberta Research Council) for helpful comments and discussion on this topic. Any errors or omissions remain my responsibility.

2007 reports that 10 such trades were completed by late 2006) and some temporary transfer activity. In 2001, a drought year in southern Alberta, trading activity took place and appeared to operate smoothly and efficiently (Nicol and Klein 2006). However, with the 2006 decision to cease accepting new applications for surface water licences in parts of the South Saskatchewan River Basin, water rights trading is the key mechanism by which future demands for water in these areas can be addressed. Within Alberta's Water for Life Strategy, there is interest in developing additional market based instruments (water pricing, etc.) to improve resource conservation and alleviate conflicts; implementing economic instruments is a goal for the medium term (2007/8 – 2009/10; http://www.waterforlife.gov.ab.ca/html/outcomes/healthy.asp).

The interest in water conservation has primarily focused on the southern region of the province because of water scarcities and the challenge of resource allocation between agricultural, municipal, industrial and other uses. The South Saskatchewan River Basin in particular has been the location of a variety of policy debates, research projects and planning exercises (Horbulyk 2007). The focus of this analysis however is on the Athabasca River basin and a somewhat different set of challenges. As the discussion above has shown, there are concerns about the degree to which water availability will be a limiting factor for economic development and the extent to which economic activity will adversely affect environmental quality in the river basin. In this section of the paper we examine a variety of approaches or mechanisms to deal with the scarcity concerns. We view these as options that should be debated and evaluated using a set of criteria for policy evaluation. In the latter sections of this paper we provide an initial evaluation using a relatively standard set of criteria. While some may view this discussion as premature given the current level of industrial activity and the availability of water, the climate change scenarios outlined above indicate that planning for potential reduced water availability and increased water quality concerns would be a prudent strategy.

2.2 *Conceptual Basis for Water Resource Allocation*

One of the challenges of water resource allocation is the multi-dimensional nature of water. Water has both stock and flow characteristics. Water has interrelated quality and quantity dimensions. Water is an important component of economic output and has economic value but it also has symbolic and cultural importance. Economists have struggled with the treatment of water as a commodity and with concepts of water value and price (Hanemann 2006). Water clearly has market value as both an input into productive processes and as an output and it has non-market value associated with ecological goods and services. It has public good and private good dimensions. One objective of policy is to allocate water to achieve the highest "value" from the resource (including environmental and market values) but the measurement required to achieve such objectives is challenging. In addition there are a number of equity concerns associated with water resource allocation including the needs of Aboriginal People and avoiding adverse impacts on sectors of society and on future generations, especially where rivers cross jurisdictional boundaries.

The challenge of water resource allocation can be viewed as a two stage process. First, given that there will be tradeoffs between economic activity and water flows, a set of objectives that balance the benefits of the economic activities and the benefits of instream water flows need to be developed. This balancing is difficult because of the diverse benefits associated with economic activities and water, the uncertainty about future economic and environmental conditions, and the diversity in needs, rights and preferences associated with water. While difficult in practice it is necessary to construct a set of objectives for water use. These may be framed as minimum instream flow needs, water management plans, determination of water needs for communities and Aboriginal People, or other strategies that provide the objectives for use as a result of the assessment of the tradeoffs associated with alternative water uses. Based on these objectives a set of mechanisms can be constructed that help guide economic activity to meet the objectives. These mechanisms provide signals through regulations, prices or other instruments that help guide the system towards the goal. There are tradeoffs associated with the choice of mechanisms as well. Some provide stronger incentives for conservation. Some are more cost effective than others – they provide a lower cost way to achieve the environmental goals. This set of tradeoffs between mechanisms is examined in detail below – in an attempt to find water allocation mechanisms that meet environmental and social goals with least cost or impact on economic goals.

If markets recognized all environmental values, they would guide water allocation in a way that meets environmental goals. While such markets do not exist, this concept of a “fully functioning market” can be used as a benchmark which maximizes the value of water use including environmental components and impacts on future resource use / availability. In this benchmark case the price of water to users includes the marginal private costs (withdrawal costs, etc.), marginal external costs (environmental costs) and the marginal user costs (impacts on future use) (Zilberman and Schoengold 2005). This conceptual approach would result in a market or an agency setting time and region varying water prices depending on the private, external and user costs. As no such market exists, nor do agencies set prices on the basis of the environmental and social costs, these aspects of water resource use go unaccounted for.

In principle, the price of water should include the impact of withdrawal or consumption on the environment. Measurement of such values, however, is clearly a challenge. While there have been many attempts to estimate components of the environmental value of water (e.g. the impact on recreational fishing values; Adamowicz et al. 1994, or recreational property values; Poor et al. 2001; see also Brown 2003) estimating the marginal value of water continues to be difficult. The measurement requires an understanding of the ecological and economic linkages between water use, hydrology, and ecosystem goods and services. Measurement of such values in the region also presents challenges. Assessing direct impacts of water quantity and quality changes on activities such as recreational fishing is possible but given the relatively low numbers of recreationists and commercial fisheries in the region these values will be relatively small. Values of traditional use by Aboriginal People are complex and difficult to measure in monetary terms. Since the human populations in the region are quite small, direct values associated with human activities such as recreation are expected to be relatively small. However, values associated with ecosystem goods and services and “passive use values” associated with fish and wildlife habitat may be significant. Unfortunately these values are the most challenging to estimate in terms of method and data collection. Increased effort in this area is to be encouraged as such analyses of the economic implications of water uses will aid in the incorporation of environmental values into planning and management decisions. At this point, and for this region, there is insufficient data to attempt to quantitatively incorporate all environmental value information into prices or to construct accurate full cost accounts for water. This continues to be an important research area that requires investment. Furthermore, this should not preclude the use of mechanisms that attempt to recognize the importance of ecosystem goods and service even if a precise measurement of their monetary value is missing.

The lack of information on environmental values rules out the direct incorporation of marginal external costs into a pricing mechanism. However, various mechanisms can be used to attempt to achieve environmental objectives in an efficient fashion. The remainder of this section examines these mechanisms. Given a target for instream flow, what mechanisms will help achieve that target and at the same time result in the least impact on economic, environmental and social objectives?

2.3 *Policy Targets and Mechanisms*

Based on the discussion above, the policy targets include maintaining instream flows in the Athabasca river and avoiding shortages (particularly seasonal shortages) that may adversely affect economic activities, communities and ecosystems. The focus here will be on water quantity recognizing that water quality is a related and critically important issue within the basin (Griffiths et al. 2006). The range of mechanisms to achieve these targets include:

- The current framework for allocation and licensing, including the recently proposed approach to recognize instream flow needs.
- Demand management approaches including:
  - Tradable water rights;
  - Water pricing, including pricing / rebate schemes;
  - Technology based standards including tradable performance standards.
- Water storage options:
  - Off-stream storage

Each of these mechanisms will be examined in light of the specific issues in the basin as well as the structure of the industry.

2.4 *Policy Options*

2.4.1 Option A: The "Status Quo"

The current framework for water resource allocation includes a mixture of permanent and temporary (term) licences for water users in the region. The recently announced water management framework for the Athabasca River includes a "green, yellow, red" scheme that implements restrictions on water withdrawals depending on the flow conditions of the river. Oilsands companies have been required to submit plans that outline how they will reduce water withdrawals at time of scarcity (http://www3.gov.ab.ca/env/water/Management/ Athabasca_RWMF/ pubs/Athabasca_RWMF_ Technical.pdf).

The discussion of the mechanisms for response to water scarcity illustrates some of the difficulties of operating within the current policy framework. If the flow conditions enter the "cautionary threshold" (yellow management zone), recent and new licences will be most directly affected as their licences will include provisions for reduced use. This continues the impact of the historical property rights that differentiate by date of licence rather than value of water use. In the red management zone condition ("potential sustainability threshold"), maximum withdrawal caps will be implemented. One approach being evaluated in this case is a restriction to a percentage of annual allocation over all licensed users (Water Management Framework 2007).

The current approach is a form of "command and control" system in which users have little incentive to reduce water use unless there is a "yellow" or "red" condition. Even when the condition of the river worsens and the reduction plans take effect, these are not implemented on a basis that recognizes that different users of water have different marginal values for water. Perhaps most importantly there are few incentives, beyond reducing private costs, for development and adoption of new technologies as there is no advantage to an individual firm for doing so (including, to a certain degree, incentives to use allocations to avoid risks of losing them – Wilkie 2005). This threshold system will help in avoiding worst-case scenarios in ecological terms, but it may do so at a very high cost to economic activity in the long run. In terms of comparison to the benchmark (where prices provide signals of scarcity) this system will not send appropriate signals to individual firms or users of water and administrative mechanisms will continue to be used to allocate water in times of scarcity. This will almost certainly be an expensive approach to water management, relative to market based mechanisms, in the long run.

2.4.2 Option B: Tradable Water Rights

Tradable or transferable water rights are emerging as a preferred instrument in various parts of the world over the past 25 years (Chong and Sunding 2006). Australia, states in the Western United States, Chile and various other jurisdictions have implemented tradable water rights. In southern Alberta the tradable water rights system is beginning to take shape helping to address the scarcity issues in the South Saskatchewan River Basin. In this section, we review the issues surrounding tradable water rights and the applicability of trading to the Athabasca case.[13]

Tradable water rights are a type of "cap and trade" system or market based instrument for environmental protection. Tradable water rights do not create an unencumbered "free market" in water, rather they provide a strict legal and administrative framework for trading water rights in a fashion that allows water to be transferred voluntarily from low value users to high value users. Maximum total withdrawals remain capped and trading is only allowed within the cap and when there are no adverse impacts on other users or on environmental quality. Typically, trading systems have approval mechanisms that provide for the assessment of impacts on third parties when such impacts are common (e.g., Section 82(3) of the *Water Act*; California's water trading system – see Chong and Sunding 2006). Tradable water rights separate the water from the land or project for which they were originally licensed, allowing entities that save water through

[13] Similar tradable permits mechanisms have been shown to provide significant cost saving in achieving environmental quality goals. For example, the U.S. SO_2 emissions permit trading market resulted in cost savings of $1B per year relative to command and control approaches (Stavins 2005).

implementation of improved technology to benefit by selling the rights to that amount of water. Rights trading has involved temporary and permanent trades in many jurisdictions and increased flexibility in the trading system tends to lead to increased frequency of trades and lower overall costs of achieving the environmental goals (Zilberman and Schoengold 2005). In Australia, temporary trades are far more numerous than permanent trades and act as effective mechanisms for addressing short term water scarcities (Bjornlund 2003). Water rights trading cannot occur without approved basin management plans (both as an enabling mechanism and for establishing environmental and distributional objectives) and without administrative systems that clearly define what is being traded and are able to monitor trades with the same security as financial institutions monitor financial accounts (Young and McColl 2003).

Tradable water rights systems have the potential to achieve water quantity goals at least cost. However, there are several potential challenges in a tradable rights system:

- Is there an ability to monitor and verify water use and enforce water use limits at low cost?
- Is the potential for third party effects substantial enough to limit the gains associated with trading?
- Will establishment of a rights trading system result in rights holders trading units that they would never have used – resulting in increased overall use of water (so called “sleeper” or “dozer” licences; Young and McColl 2003.)?
- How will the trading system account for rights with differing priority dates (e.g., permanent old licences versus temporary new licences)? In principle the market can be designed to differentiate between different types of licences, but this will make the market more complex and potentially limit the number of transactions (reducing the efficiency of the market). An alternative is to “buy back” senior water rights in exchange for term rights that may facilitate trading and a simpler market.
- Will there be sufficient heterogeneity in water value to the firms involved in the market to result in trades? If there is no variation in firms’ technologies or activities then there will be no gains from trading – the system will essentially be a command and control mechanism. A somewhat related issue is the question of the extent of the market. Typically an intrabasin market only is considered, but the set of industries, municipalities and other users to be included will have to be determined. In addition, sufficient water for communities and ecosystem services will have to be maintained. Will such a market include the possibility of trades outside of the province (Horbulyk 2005 discusses issues surrounding an interprovincial trading scheme for water).
- How will the initial set of rights be allocated? It is most common to distribute the initial tradable rights on the basis of historical use (Tietenberg 2001). However, in protecting their historical rights and investments, this also provides existing rights holders with a windfall gain of an asset – however this pattern of gains may be similar to the gains that would arise from establishing a market. Auction mechanisms have also been proposed but seldom used. Given the recently rapid development of the oilsands area an approach based on historical allocation would seem problematic in that barriers to entry in an imperfectly competitive system may arise. There is considerable literature on the

potential difficulties in cases with imperfect competition on the output or tradable rights market (Requate 2005).

- Will the system be designed with sufficient interest paid to fundamental water needs for people and the environment in the region, and in particular to Aboriginal Peoples' rights associated with water and the environment, both in Alberta and the Northwest Territories? Associated with these equity and environmental concerns, will the tradable water rights system provide the opportunity for the government or other parties (e.g., Environmental Non-governmental Organizations) to participate in the market and hold water rights to remain in the river and enhance environmental quality? In California, for example, the government frequently intervenes in the water market making purchases to address environmental concern (Chong and Sunding 2006 state that in California in 2001, one third of the water rights trades were for environmental purchases).
- Water rights trading may provide incentives to construct and implement storage to offset seasonal variability. Brennan (undated; 2006) describes how water storage markets may emerge from storage that serves multiple firms – increasing the efficiency of resource allocation over time.

This long list of design issues suggests that tradable water rights will need to be carefully designed for this region. However, there is evidence from other parts of the world that tradable water rights systems can be established with relatively low transactions costs, with mechanisms to reduce or address third party effects and with the flexibility of both permanent and temporary transfers that help reduce the costs of achieving social, economic and environmental goals for water.[14]

In the case of the Athabasca, the key issues include the definition of the cap or maximum amount of withdrawal in a fashion that recognizes the seasonal nature of the water scarcities, long term variations in water flows arising from climate change and other factors, and the equity and environmental issues. Establishment of the cap also requires the development of an approved water management plan for at least this part of the Athabasca River and the plan would also be used to allow licence transfers, provide for holdbacks on trades (if required), and establish how any unallocated water in excess of the cap will be managed. The initial allocation of rights can be based on historical use or some other criteria, however, as mentioned above, this creates some difficulties in a rapidly evolving economy such as that of the oilsands area. The relationship between the current priority rights system, the heterogeneity of rights (those that do not expire versus those that do; priority order) and a trading system must be defined. This transition may be quite challenging (M. Young, Professor and Research Chair in Water and Water Management, University of Adelaide, personal communication, March 2007). Some innovative systems for addressing equity issues have been proposed elsewhere. M. Young (2007, personal communication) described a system in which a percentage of water allocation was reserved for

[14] There is a large literature on emissions trading that applies to the case of water rights trading and market based approaches to water resource allocation. The analysis of mechanisms for allocation of initial rights or for recycling revenues from auctions or charges in the emissions control case for example will inform the design of mechanisms in water resource allocations. Summaries of this literature can be found in NCEE (2001), European Environment Agency (2006) and Stavins (2001). A survey of approaches including the case of water allocation can be found in NCEE (2004).

auctions, with the proceeds going to Aboriginal People to address water treatment or other community needs. Water rights trading is increasing in popularity in various jurisdictions, and Alberta is beginning to embrace water trading in the south, yet there remain issues particular to the Athabasca river that present challenges.

2.4.3 Option C: Water Charges

While water rights trading puts a constraint on the quantity of water available and prices emerge from the market, water pricing attempts to simulate a market by setting charges that account for the environmental and user cost (future use) components of water. In principle, a set of time and spatially varying charges that were based on knowledge of the environmental and user costs could result in perfect correspondence with the benchmark of water resource allocation that economists consider efficient use.[15] In practice, setting charges will have to be based on estimates of these impacts. Water pricing does not directly provide limits to water use the way that tradable rights do, but prices provide signals that would encourage demand management, such as reduced use and adoption of technology to reduce use. Water pricing may also provide signals for supply management, such as the development of storage structures and storage markets. Pricing requires metering and reporting of use (ideally withdrawals less return flows – Horbulyk 2005) – something that is already in place for most oilsands uses (Griffiths et al. 2006).

Three issues that arise with the use of charges are: (1) the responsiveness of water use to charges; (2) the cost implications for firms; and (3) the use of the revenues from the water charges (see Griffiths et al 2006 for additional discussion). There is evidence that increases in costs of water do result in substitution of other technologies (recycling, recirculation, etc) and reduced use (Renzetti and Dupont 2001). Renzetti (2005) suggests that industry responsiveness to increases in water costs may be more sensitive than agricultural or residential sectors. Renzetti (2005) provides an average estimate of the price elasticity of water intake (% change in water intake for a 1% change in water price) for Canadian manufacturing sectors of -0.80.[16] Dupont and Renzetti (2001) report ranges that are somewhat smaller in magnitude (-.015 to -0.59). Renzetti (2005) also cautions that there is some evidence of a substitution effect between water and energy and thus if some form of “carbon tax” were implemented it might result in increased water use. Regarding the extent to which increases in water costs will affect the overall costs in the sector, Renzetti (2005) shows that industrial water costs in Canada in general make up a small proportion of overall costs. Dupont and Renzetti (1999) state that modest water prices may only have minor effects on overall costs. For example, they suggest that after imposition of a \$0.003 per m^3 water price, water costs in Ontario manufacturing would increase from 0.01% of costs to 0.2% of costs. Note that these are estimates for the manufacturing sector - this is an issue that will need to be studied more closely for the oilsands sector. Information on elasticities, impacts of pricing strategies and potential for substitution / technical change will be required to develop a successful pricing approach (Griffiths, et al. 2006; Renzetti 2005).

[15] In addition the system of charges would have to differentiate between surface water, ground water and saline water use – see discussion below.
[16] Note however that this is an elasticity of withdrawals and not of “uses” of water. The latter will be more important for policy analysis.

The final issues in pricing are the establishment of the price levels and the use of the revenues from water charges. As a simple example, using the estimates from above of 15 cubic metres per second of water use at maximum production levels, modest charges ($.03 to $.05 per m^3) would yield between approximately $14M and $23M per year if no changes in use occurred. These are within the range of charges for water in agricultural or irrigation cases (OECD 2002 – Transition to full cost pricing of irrigation water for agriculture in OECD countries) or in some industrial settings (OECD 2004 – Competition and regulation in the water sector). However, substantially larger prices (an order of magnitude larger) have been observed as typical industrial and municipal water charges in other parts of the world[17] (e.g., for Australian water tariffs http://www.esc.vic.gov.au/public/Water/Regulation+and+Compliance/Tariff+Approvals/Tariff+Schedules/) and in temporary trades in Australian water markets (Brennan 2006). Water charges in this range will have an impact on the cost of production of energy resources – depending on the degree of substitution and the potential for technical innovation. The opportunities for recycling, water substitution (between surface water, ground water and saline water), substitution of other inputs for water, and process innovations are important factors to assess if a system of water charges is to be used.

An issue arising from the use of charges is the use of the revenues raised. Typically these revenues go to general revenues in a jurisdiction, maximizing the flexibility of the use of the funds. Increasingly, there has been interest in earmarking such revenues for environmental projects, to reduce impacts on affected third parties, or for other uses. An intriguing scheme used in Sweden to provide incentives for the reduction of NO_x is a Refunded Emissions Payments Scheme (REP) (Sterner and Hoglund Isaksson 2006). This scheme charges industry per unit of NO_x emitted, but refunds (a large portion of) the revenue to the industry on the basis of the output of the industry (measured in terms of energy production in the Swedish case).[18] The REP scheme provides incentives for reduced "emissions" yet recycles the revenue to the same industry, softening the blow in terms of impact on firms (making the scheme more acceptable to the sector) and allowing firms to compete in terms of the share of the recycled revenue. Since firms are taxed on emissions but revenues are recycled on outputs (or intensities), this encourages reductions in emissions intensity but does so by directly targeting the emissions. In terms of comparison with the benchmark case in which water is priced in terms of the marginal environmental damage and the marginal user cost, the REP scheme is not efficient relative to the benchmark as firms can capture the revenues generating an output effect (Fisher, 2001; Bernard et al 2006). However, in some cases (imperfect competition – or few firms in the output market) these schemes have desirable properties (Gersbach and Requate, 2004). On the other hand when firms have a relatively large share of output this scheme sends less of a conservation signal (Sterner and Hoglund Isaksson 2006). Sterner and Hoglund Isaksson (2006) review the Swedish experience with the REP and argue that in terms of acceptance of the mechanism and effectiveness in reducing overall emissions, the approach has been very

[17] Dinar (1997) lists industrial water prices in Canada as ranging from $0.17 to$1.52 / m^3 (1996 US $) with global examples ranging from zero to $7.82/ m^3 (1996 US $) but these are somewhat dated values.

[18] Alternative forms of this scheme have been proposed including refunding on the basis of the share of output over the share of "emissions". The net effects (refund less charge) to the average firm would be zero while firms with higher outputs per emission shares (or higher environmental effectiveness) would receive refunds and firms lower in outputs per emission shares would have net payments.

effective. Over an 8 year period (1992 – 2000) emissions were reduced by 40% (Sterner and Hoglund Isaksson, 2006).

Notable design features in the Swedish NO_x case are that a large price was charged per unit of emissions (the prices were approximately $6000US / ton compared to typical charges in non-refunded schemes of $150 - $100 US / ton; Sterner and Hoglund Isaksson, 2006).[19] This large charge was chosen to induce reductions and technical change in the sector. Without recycling this large charge would likely not have been feasible. Secondly, a small fraction of the collected revenue (2-3%) was used for administrative and monitoring purposes (Sterner and Hoglund Isaksson 2006). This meant that the vast majority of the revenues were recycled. There are "winners and losers" in this scheme – but in aggregate the sector is largely unaffected yet the incentive to reduce emissions is maintained. There were concerns that the scheme would lead to output effects but since the size of the charges relative to overall costs were low and there were opportunities for reductions in emissions, these impacts were minor (Sterner and Hoglund Isaksson 2006). This scheme has many properties that are similar to a tradable permits scheme with permits allocated based on historical output levels – but without many of the transactions costs associated with tradable permits schemes.

Such a REP scheme might be effective in the case of water fees in the oilsands region. It would be relatively easy to determine the output used to recycle the revenues and it would lessen the impact on a sector that may be facing various other costs associated with environmental effects. The prices or charges could be large enough to induce significant water conservation practices yet the recycling would allow firms to compete in intensity terms to capture the returns. The monitoring and enforcements costs would be relatively low as water use and outputs are currently tracked and monitored. A remaining research question is the extent to which this recycling scheme for reduction of use of an "input" (water) would differ theoretically from recycling schemes based on reductions of an emission. The remaining design issues include the establishment of the level of a charge (including provision to adjust for inflation and changing supply and demand over time), the extent of the program (which sectors or industries are included in the program), the portion of the revenue that is not recycled, and the establishing the appropriate mechanism that would allow earmarking of revenues. Regarding the portion of revenue not recycled these amounts could be used to provide support for parties adversely affected by water use (e.g., Aboriginal communities in the region), to support environmental improvements through projects and research, and to fund administration of the program.

2.4.4 Option D: Performance Standards and Tradable Performance Standards

A common approach to encourage firms to reduce emissions (or water use) is to implement performance standards or targets. For example, a target or goal for the number of barrels of water required to produce a barrel of oil at a level lower than the current industry average might be developed for the sector with disclosure on progress towards this goal. Firms could be encouraged to achieve these targets voluntarily, by setting technology based standards, by

[19] Prices from NOx trading in the U.S. SIP (State Implementation Plan) program in 2004 were in the range of $2,500 /ton (http://www.epa.gov/airtrends/2005/ozonenbp/onbpchap4.pdf#page=1)

subsidizing technology to help achieve the goal, and/or by incentive based mechanisms associated with deviations from the target.

Experience with voluntary standards has met with mixed reviews at best. Harrison and Antewiler (2003) describe the relatively weak performance of some voluntary pollution control mechanisms in Canada. On the other hand the energy sector in Alberta has made significant progress in reducing water use per unit output (CAPP 2002). In general economists are concerned about the lack of incentives associated with voluntary approaches, subsidies, or technology based standards. The latter provide little incentive to improve beyond the standard and the standards tend to be based on negotiations that do not typically meet the benchmark for efficient treatment of emissions – although there is some evidence that voluntary standard setting can result in more flexibility for firms in achieving the standard (Khana 2001; Anton et al. 2004). Subsidies can help result in the adoption of technology but they do not send the correct signals regarding conservation. These concerns translate directly to the case of water use.

Tradable performance standards are a slightly different case. In this case the desired emissions intensity (emissions per unit output) is set as a target. If a firm has an emissions intensity lower than this target they can sell some “permits” up to the point where they meet the intensity target. If a firm is above the target they must buy “permits” to reduce their intensity to the target (Fisher 2001; 2003). This scheme, when applied to water, has many parallels to the case of tradable water rights with initial allocations based on output levels, or to the REP scheme in that a firm’s water use and their output (oil production) factor into the mechanism to achieve the target. As in the case of the REP scheme, tradable performance standards do not achieve the level of the benchmark of economic efficiency (Fisher 2001). The most important difference between these three schemes is the way that they set targets or employ charges to reach targets. In the case of tradable water rights with free initial allocation – the key design feature is the “cap” and maximum water allocation. The mechanism maximizes water use efficiency within the cap. With the REP scheme, the key design feature is the water charge and the mechanism sends signals for efficient use of water but does not explicitly cap water use. A supplementary framework is required to implement the cap. In the case of tradable performance standards the key feature is the target water use per unit output (or water use intensity) and as with water charges supporting regulations are required to limit water use to be within a cap. The choice of instrument depends in large part on the desirability of each of these mechanisms and the feasibility / transactions costs of the approach.

2.4.5 Option E: Water Storage – A Technology Based Option

One mechanism to deal with the scarcity of water in winter in the Athabasca basin is the construction of off-stream storage sufficient to meet winter flow needs. Griffiths et al. (2006) describe off-stream storage as a feasible option to address low flows. A study undertaken by Golder Associates (2004) also concluded that off-stream storage represented a practical solution for addressing low winter flows in the Athabasca River. Golder Associates (2004) estimates costs of \$0.50 m^3 to develop sufficient storage to address current concerns. The ecological aspects of such storage should be an avenue for further research – as should the assessment of costs, funding and management options for off-stream storage developments.

A strategy that may lead to desirable outcomes is one that signals the scarcity of water in low flow periods to which firms may respond by constructing storage. For example, a system of water charges that is low for high flow periods and higher for low flow periods would provide incentives to conserve water and to shift water withdrawals in time. Storage would be one logical option in this case and collaboration to develop off-stream storage may result.

2.5 *Scope of Application of the Mechanisms*

The mechanisms described above discuss impacts on the economy, and impacts on water use, in general terms. Detailed assessments of which components of the economy are included in each mechanism are required. For example, in the case of water charges, which economic sectors (oilsands, conventional oil, forestry?) are to be included? If a large "unregulated" sector exists then perverse incentives can arise and the mechanisms may not operate as desired (Bernard et al. 2005). However, the transactions costs associated with the incorporation of all economic entities may be high. Also, the discussion above has focused on surface water but there are important interactions between surface water, ground water and saline water. In the case of tradable rights, trading may differentiate between sources of water. In the case of charges, differential or relative water charges would likely have to be established on all water sources to provide signals for conservation. These are important design elements that apply to all mechanisms.

2.6 *Evaluation of Mechanisms*

A variety of options have been presented and some of these options could be considered in combinations. As with any set of options there are tradeoffs between aspects of the options. Olewiler (2007) provides a policy evaluation framework that facilitates a comparison of policy options on the following dimensions:

- Economic efficiency / cost effectiveness (comparison with the economic benchmark described above; is there an incentive to reduce water consumption?).
- Political feasibility (are there conflicts with existing policies, ministry strategies, etc. will the approach remain feasible through fluctuating environmental, economic or social conditions?).
- Stakeholder acceptance (is there support from the industrial sector for the mechanism relative to other mechanisms?).
- Public acceptance (is there public support or challenges to the proposed approach?).
- Impact on environmental goal (will the environmental goal – maintaining adequate water flows for ecological function and economic activity – be met?).
- Implementation cost / transactions costs (what are the costs of designing the system to support the approach?).
- Adverse selection (would the water have been conserved without such policies – implicitly penalizing those acting to conserve water before the implementation of the mechanism?).

- Complexity and cost of monitoring / enforcement.
- Equity (will affected firms be treated fairly; will the approach have adverse effects on other users; will the condition of land and waters for use by Aboriginal People be improved or degraded by the mechanism?).
- Long term prospects (will the policy provide long term protection for the environmental goal in the face of climate change, changing demand and supply of water, changing economic conditions, changing technologies, etc.?).

The following matrix summarizes the options and the evaluation criteria. While the evaluation provided is qualitative and there are several questions that require additional information to fully complete the matrix, the evaluation framework provides some insights into desirable and undesirable aspects of each of the options.

Option	Economic efficiency	Political feasibility	Stakeholder acceptance	Public acceptance	Impact on environmental goal	Implementation cost / transactions costs	Adverse selection	Complexity and cost of monitoring/ enforcement	Equity	Long term prospects
Current Approach	Incentives for conservation based on private costs and voluntary actions. Not economically efficient	Clearly feasible but there are discussions regarding the need for improvements	Stakeholder strategies to respond to scarcity are being developed – implies some level of acceptance	Mixed views.	Unlikely to achieve the environmental goal without voluntary actions or significant technological advance.	N/A	N/A	Low	Inter and intra generational equity concerns.	Unlikely to be viable over the long term
Tradable Water Rights	May be very efficient depending on the design.	Currently being utilized in southern Alberta – consistent with Water for Life strategy	May be acceptable depending on the design.	Generally acceptable with some reservations on equity grounds. The public would likely be in general support of water trading.	Environmental goal defined by the “cap” – meets environmental goal by definition	Depends on design – may be significant in developing approved water management plan and trading system; ongoing costs unlikely to be much different than under status quo	May penalize those who have improved conservation practices – depending on design	Moderate	Concerns based on initial allocations of rights and third party effects (on other users, communities, Aboriginal People).	Very good long term prospects of meeting the environmental goal at low cost. Provides some resilience or ability to adapt to climate change impacts and changing supply and demand conditions.
Water Charges – with recycling of revenues	May be very efficient depending on the design. Some concerns about undesirable effects from the revenue recycling schemes.	Unlikely to be feasible unless the policy addresses fairness between industry sectors and/or recycles revenues.	May be acceptable depending on the design – but likely less acceptable than tradable water rights.	Support for environmental improvements but there may be concerns regarding the use of revenues and recycling (e.g. distribution, earmarking).	Does not necessarily meet environmental goal – depends on level of charge and use of time varying charge and/or a supplemental cap on water use.	Modest – water use and output are monitored.	May penalize those who have improved conservation practices – depending on design	Low	Concerns may arise regarding differential impacts on firms / industrial sectors. Concerns may also arise from the use of the revenues	Good long term prospects of meeting the environmental goal at low cost. Provides some resilience or ability to adapt to climate change impacts.

Option	Economic efficiency	Political feasibility	Stakeholder acceptance	Public acceptance	Impact on environmental goal	Implementation cost / transactions costs	Adverse selection	Complexity and cost of monitoring/ enforcement	Equity	Long term prospects
Performance standards	Not efficient. Can be improved if incorporated into a market based scheme but will not be as effective as a fully functioning tradable water rights approach.	Feasible – similar approaches have been employed in other environmental policies. Incentive based scheme will be less feasible	May be acceptable	Generally acceptable as long as environmental quality improves.	Does not necessarily meet environmental goal – depends on efficacy of implementing performance standards and level of industry growth.	Modest – depending on design	May penalize those who have improved conservation practices – depending on design	Low to Moderate	Depending on the standards established – there may be concerns within industrial sectors and/or concerns by communities, Aboriginal People	May be viable over the long term but will not result in a cost effective outcome.
Technology Options – Off stream storage	Does not provide conservation signals per unit of water but may provide a solution to seasonal shortages. May be the outcome of an efficient water charge strategy.	Feasible	Probably acceptable depending on cost.	May be acceptable as long as environmental quality improves.	May meet environmental goal – especially if in concert with other instruments (e.g. charges, defined limits on use)	Potentially significant implementation costs	Depending on approach and costs sharing – may have negative effects on some.	Low	Depends on the location and ecological impact – may generate significant concerns from communities / Aboriginal People.	May be viable in the long term depending on the degree to which storage can address low flow levels and if the ecological effects of storage are low.

2.7 *Conclusions*

This paper has provided an assessment of the water flows in the Athabasca River with projections of the impact that climate change and increased industrial activity may have on the river. Given the potential for significant water scarcity in the river and associated impacts on the potential for economic growth and environmental quality, a set of options for managing water scarcity was presented. An initial attempt to evaluate these options has also been provided. The following summarizes the recommendations.

A key first step should be to complete the development of a basin management plan to identify the distributional and environmental goals of water allocation and to enable the development of mechanisms for conservation – providing incentives for reuse, recycling, and substitution of scarce water resources.

To attain long term economic, social and environmental goals it is likely that one or a combination of mechanisms will have to be implemented. In the absence of a cap on withdrawals, a combination of a seasonally adjusted water charges with development of off-stream storage may be able to achieve the water quantity goals by providing incentives for conservation and development of cost-effective technological options. If a cap on withdrawals in established, transferable water rights may be able to provide signals for technological improvement and generate cost effective solutions, while clearly protecting the Athabasca's instream flow needs. A system of charges may be a short term solution while the development of the trading system occurs.

Both trading and charging mechanisms have desirable properties in terms of resource conservation. A combination and/or sequencing of charges and trading may also provide significant benefits in terms of conservation and in meeting the environmental goals at least cost. An important issue to consider is the degree to which these mechanisms provide resilience or ability to adapt to climate change (and to economic and environmental shocks in general). Climate change will undoubtedly affect the economy of Northern Alberta through water and other changes – but a system that signals the scarcity of resources to users through prices (water prices or tradable permit prices) will be able to adapt and innovate in the face of change.

A number of topics have not been adequately addressed in this paper, including the need for research on the environmental value of water, impacts of policy and mechanisms on communities and Aboriginal People both in Alberta and the Northwest Territories, the degree to which on-going technological change in the sector will address water quantity challenges, and instream flow needs for the basin. In addition, this paper has focused on water quantity while water quality concerns also require attention. Nevertheless we hope the objectives of this paper – to evaluate concerns regarding the region's water flows and to provide a set of options, will begin a discussion and debate on the best approaches to address water resource concerns on the Athabasca River while maintaining the opportunities for economic growth, community development and environmental quality improvement.

2.8 *References*

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