HYDROTECHNICAL RESEARCH IN THE ALBERTA OIL SANDS

by

D.T. SNEDDON

Research Management Division
Alberta Environment

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by D.T. Sneddon, Research Management Division,
Alberta Environment,
9820 - 106 Street, Edmonton

ABSTRACT

Hydrotechnical research in the Alberta Oil Sands has been oriented toward establishment of baseline (i.e. predevelopment) environmental conditions and identification of contaminant transport mechanisms. Monitoring networks for both groundwaters and surface waters are in place and both water yield and quality are being observed. Plans are being made for research into groundwater/surface water interaction and into the geomechanical consequences of in situ extraction of bitumen using high pressure, high temperature steam injection techniques.

1.1 LOCATION OF DEPOSITS

The Alberta Oil Sands consist of five geologically and geographically separate entities. These are shown in Figure 1. While some industrial activity is underway in each deposit, environmental research is being actively pursued by Alberta Environment in only the two most active deposits, Athabasca and Cold Lake. Since all the deposits are located in the Boreal Forest life zone, it is hoped the knowledge and principles established in the two most active deposits will also apply to the remaining three.

Most of the environmental research carried out to date has been in the Athabasca deposit. Therefore, the bulk of the present paper concentrates on that region.

1.2 GEOGRAPHY OF THE ATHABASCA DEPOSIT REGION

1.2.1 Physiography

The physiographic sub-provinces shown in figure 2 were defined by Thompson et al (1978) on the basis of terrain analysis of aerial photography and remote sensing imagery. To put them in a regional context (that suggested by Bostock (1968)), the Birch Mountains Uplands and the Algar Plain, form part of the Alberta Plateau; the Stony Mountain Upland and Methy Portage Plain sub-provinces are in the Alberta Plain physiographic province; the Clearwater Lowland, Firebag Plain and Muskeg Mountain Upland are part of the Saskatchewan Plain; and the Athabasca Delta Plain and Athabasca Plain are part of the Great Slave Plain.

The upland areas are typically hummocky disintegration moraine overlying soft cretaceous sandstones, siltstones and shales of the Grand Rapids and Clearwater formations. These overly the bituminous McMurray formation locked sands and interbedded clay shales of fluvial origin.

The upland areas are also typically well drained and represent regional groundwater recharge areas, while the lowlands are muskeg peat bogs and are groundwater discharge zones. Discontinuous permafrost occurs throughout the region.

The Athabasca River roughly bisects the study area and represents the reach of interest of the mainstem Athabasca. The outlet channels from Lake Athabasca to the Slave River have also been included in the study area. Nineteen tributary basins have been delineated for the study area, as shown in figure 3. The principal hydrometric stations are also shown in figure 3.

1.2.2 Access

Access to the region is still relatively poor. A paved all weather highway extends from Fort McMurray to Fort MacKay, which is located about 70 km to the north. A bridge over the Athabasca has recently been constructed at Fort MacKay, providing direct access to an all-weather network of lease roads on the east side of the Athabasca River. A new town has been planned for the east side of the river to accommodate people working at the proposed Alsands and Canstar projects. These are recent developments, however, and most of the work described below was logistically supported by air.

1.2.3 Climate

The Climatology of the Athabasca region has been reported by Longley and Janz (1978), who describe the climate as being similar the central regions of Alberta although cooler and lacking chinooks.

Summers are short but warm and daytime highs in excess of 30°C can occur in July and August. About 2/3 of annual precipitation occurs in the summer months, mostly in the form of thunder shower activity. Precipitation intensities of 3 mm/hr over a 24 hour period have been recorded and are estimated to have a ten year return period.

Instantaneous (5 min.) intensities of 110 mm/hr are estimated to have a 25 year return period in the region surrounding Fort McMurray. The 2 year return period design storm would be expected to have a five minute duration intensity of 63.5 mm. Intermediate intensities are shown in table 1. Verschuren and Wojtiw (1980) suggest the frequency of high intensity storms to be much higher than the climatic records show, due to the historically low density of precipitation guages in the region. Snow depths in the region average about 46 cm (table 2).

Wind velocities average about 10 km/h and are dominantly from the west in all seasons.

Table 1: Short-duration rainfall-intensity data for Fort McMurray A. Source: Longley and Janz (1978).

Rainfall Rates in mm/h

Return Period Years	5 min	10 min	15 min	30 min	1 h	2 h	6 h	12 h	24 h
2	63.5	46.5	37.1	22.9	13.5	8.8	4.6	2.8	1.7
5	82.3	62.0	55.2	32.8	19.0	13.5	6.8	4.2	2.4
10	94.5	72.4	65.5	39.4	22.6	16.7	8.2	5.2	2.9
25	110.2	85.6	79.0	47.8	27.2	20.6	10.2	6.4	3.6

Rainfall Amounts (mm)

Return Period Years	5 min	10 min	15 min	30 min	1 h	2 h	6 h	12 h	24 h
2	5.3	7.8	9.3	11.5	13.5	17.7	27.6	33.6	43.2
5	6.9	10.3	13.8	16.4	19.0	27.0	40.8	50.4	61.0
10	7.9	12.1	16.8	19.7	22.6	33.4	49.2	62.4	73.7
25	9.2	14.3	19.8	23.9	27.2	41.1	60.0	76.8	91.4

Table 2. Snow cover (2.5 cm or more) statistics for Fort McMurray A and Embarras. Source: Longley and Janz (1978).

	Date of first snow cover	Days with snow cover	Date of last snow cover	Date of first snow cover	Days with snow cover	Date of last snow cover
Earliest or least	5 Oct.	127	27 Mar.	11 Sep.	127	3 Apr.
Mean	31 Oct.	154	17 Apr.	17 Oct.	171	28 Apr.
Latest or most	2 Dec.	186	12 May	1 Dec.	199	27 May
	Least	Mean	Maximum	Least	Mean	Maximum
Maximum depth	23	46	104	28	48	66

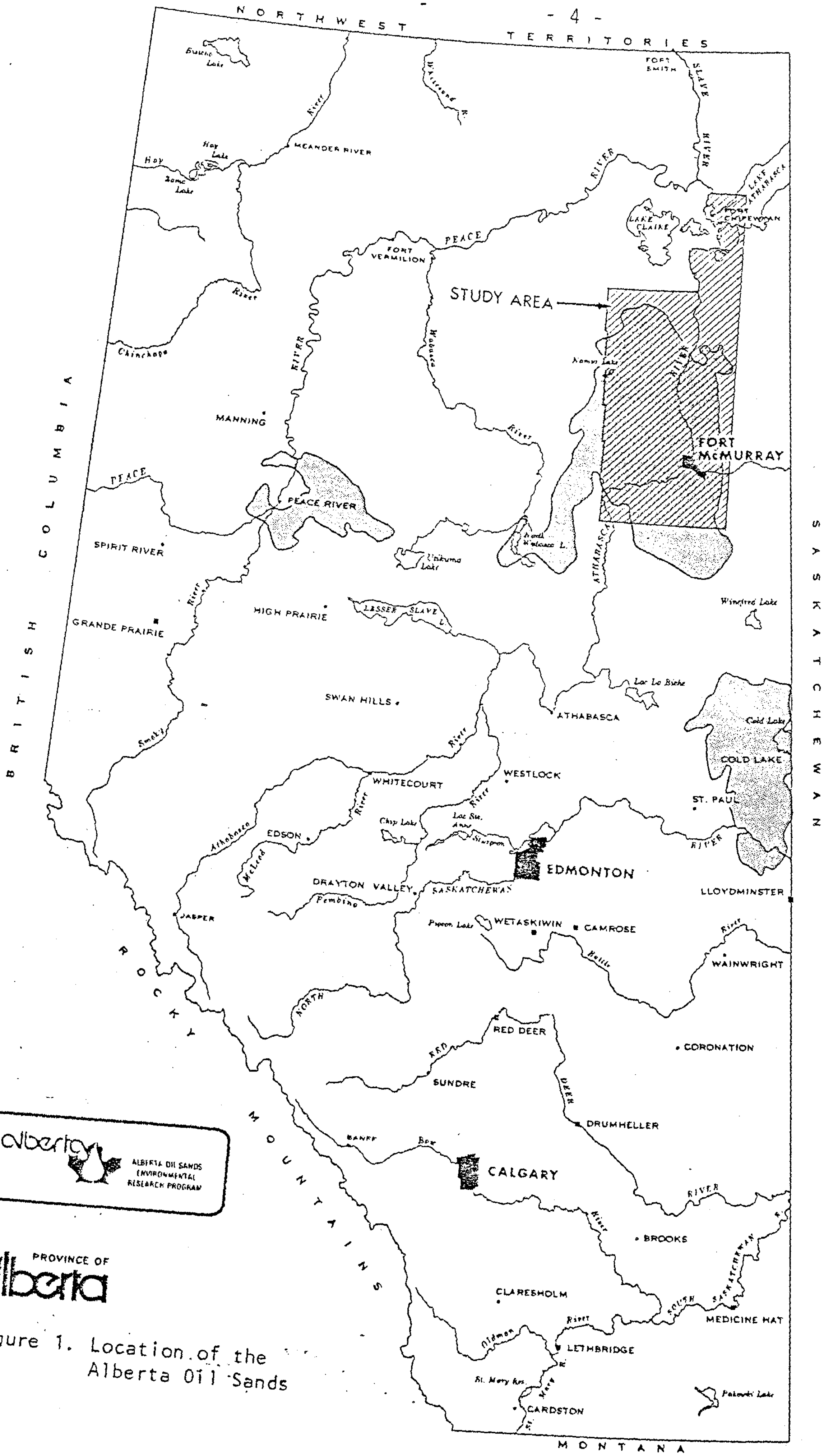

Figure 1. Location of the Alberta Oil Sands

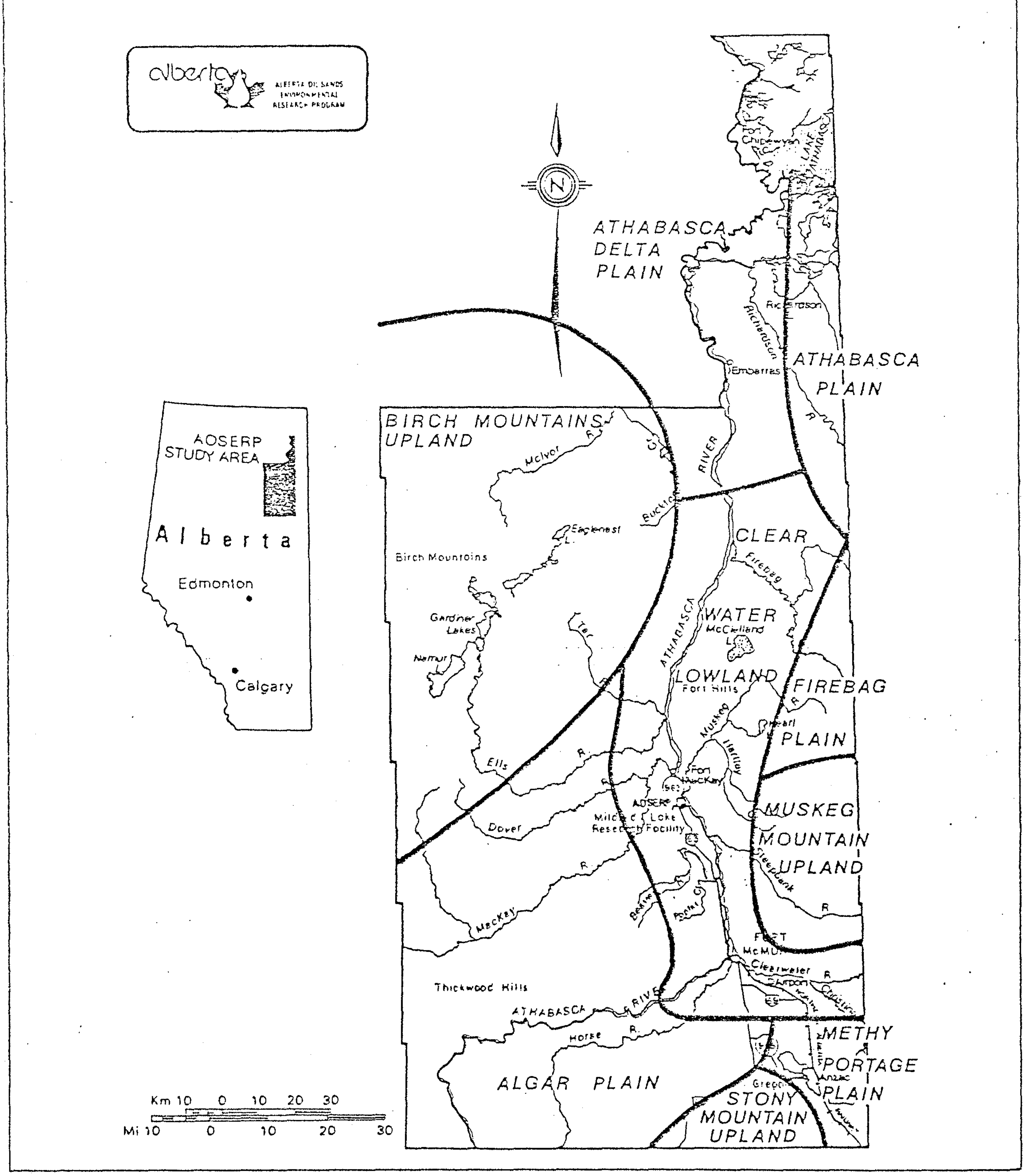

FIG. 2 PHYSIOGRAPHY OF THE AOSERP STUDY AREA.

(After Thompson et al. 1978)

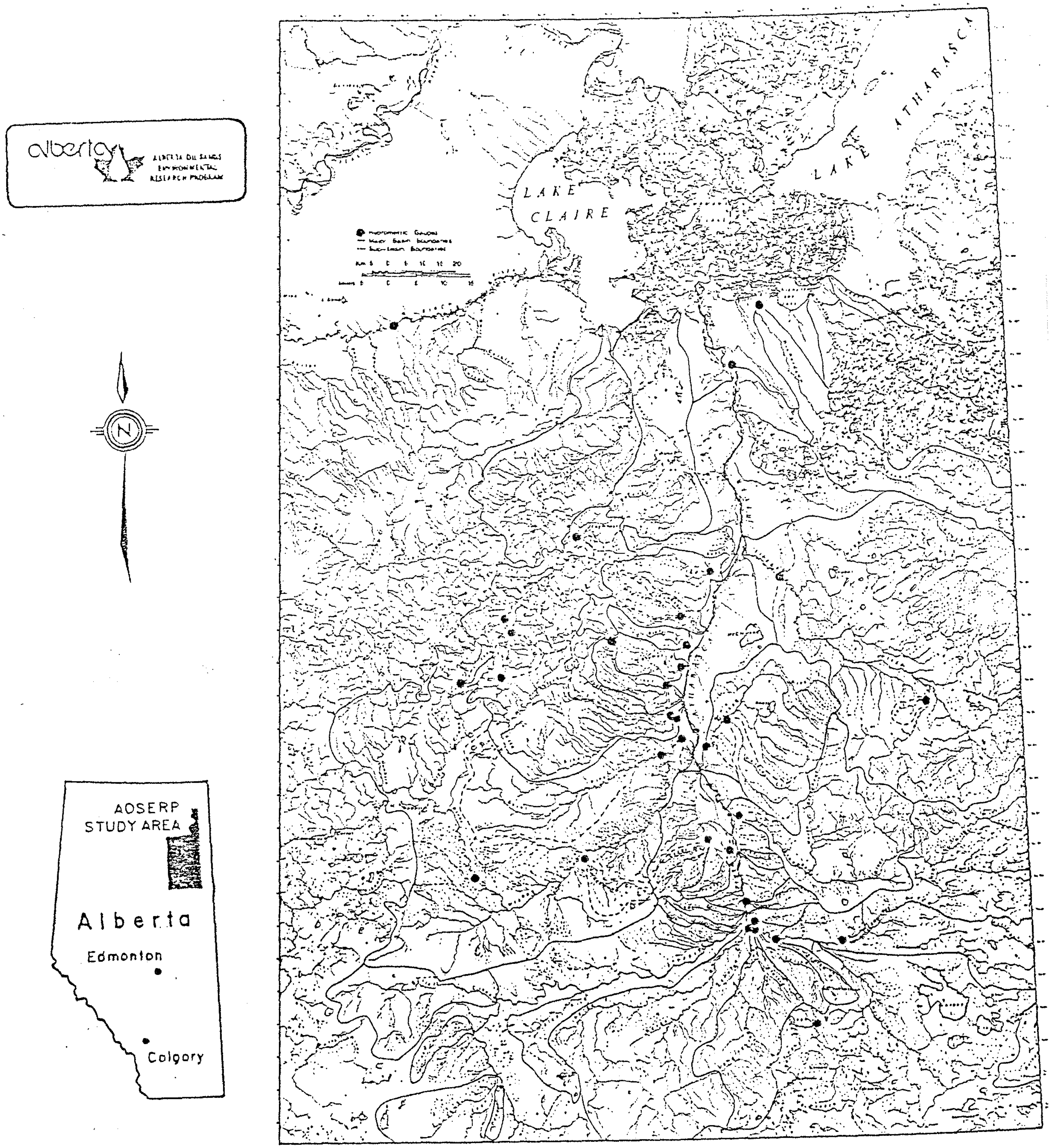

FIGURE 3. AOSERP HYDROMETRIC AND WATER QUALITY MONITERING NETWORK

Topography is an influence on the mesoclimatology of the region. Davison et al (1981) noted that terrain such as Birch Mountain and Muskeg Mountain influence wind velocity to about 400 m above the ground, particularly in winter. This has some significance for the spatial distribution of snow cover and pollutants from bitumen upgrading plants according to Murray (1981), which may in turn influence water quality during the spring runoff.

Hours of sunshine data suggest the region is about average for locations in mid-Canada.

1.2.4 Soils

A soil survey for forestry, agricultural and engineering uses has been carried out for AOSERP by the scale of 1:126,720 (Turchenek and Lindsay, 1981) from manuscript maps prepared at a scale of 1:50,000. In addition, surficial geology maps have also been prepared at a scale of 1:50,000 derived from aerial photography, remote sensing data and limited ground truthing by Thompson et al.(1978).

In general, the area is mantled with organic soils overlying glacial and post-glacial parent materials. In particular, the lowland areas are dominated by lacusterine sediments and the highlands are capped with glacial till. Abandoned beaches are found between elevations 312 and 511 metres above sea level. These elevations are taken to be the maximum extent of the glacial lakes. Post glacial eolian activity produced extensive dune fields in the northern part of the region, some of which are currently active. The infiltration capacities of the various soil groups have not been reported.

1.3 THE OBJECTIVES FOR THE ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM

The Alberta Oil Sands Environmental Research Program (AOSERP) was begun in 1975. The purpose for the Program was to "...provide timely information about factors that will aid... (The Alberta and federal governments) in establishing guidelines for socially acceptable limits of damage to present and potential uses of biotic and abiotic resources," in the words of the 1977 Canada-Alberta Agreement.

It was initially a cooperative federal-provincial study, however the federal government withdrew in 1979, before the study was complete. The general and specific objectives for the Program are available from the Research Management Division, as are the original Terms of Reference under the Agreement.

The first five years of work were oriented toward gathering pre-development ("baseline") data on the Athabasca deposit. This priority was struck in response to the obvious environmental disruption caused by large scale open pit mining, already underway at the Great Canadian Oil Sands (now Suncor) lease since 1967 and proposed for the Imperial Oil leases by the Syncrude consortium.

Following the withdrawal of federal support for the Program, it was extended to include the Cold Lake region as well. To date, baseline data for Cold Lake has been collected entirely in support of the Cold Lake-Beaver River Water Demand Study, with the exception of seismicity data, which will be discussed below.

1.4 GOALS FOR HYDROTECHNICAL RESEARCH

The hydrotechnical component of AOSERP was proposed well before the inception of the Program by the Oil Sands Hydrological Research Task Force of the Conservation and Utilization Committee of the Alberta Natural Resources Coordinating Council, in July of 1973. The Task Force recommended a two phase approach consisting of:

(1) an inventory of the hydrologic resources in the drainage basins likely to be affected by mining in the near future, and also in the Peace-Athabasca delta, and

(2) a detailed examination of existing operations, to study water use and water wastes, including drainage of mining areas, tailings ponds, etc.

The Task Force also recommended a series of specific lines of enquiry to be pursued (Thiessen, 1974). These research needs were predicated on one key issue: the nature and disposition of tailings pond effluents. In situ exploitation of bitumen was not considered by the Task Force, although one pilot plant (the Amoco Gregoire Lake operation) was in operation at the time they met.

In addition, supplementary studies on the evapotranspiration characteristics of resident plant communities were proposed to assist with reclamation of mine tailings.

These fundamental goals, with modifications to explore the implications of in situ bitumen development technology on groundwater regimes, have been carried forward to the present. specifically, the present goals are:

a) To numerically model the mainstem, Athabasca Delta and Lake Athabasca system.

b) To identify and quantify the source, fate and effect of contaminants.

c) In cooperation with Earth Sciences Division, to determine the relationships between surface and ground water.

d) In cooperation with Earth Sciences Division, Alberta Oil Sands Technology and Research Authority (AOSTRA), Alberta Environmental Centre, Vegreville (AECV) and Alberta Research Council (ARC), to assess the environmental consequences of in situ bitumen extraction technology.

e) In cooperation with the Pollution Control Divison, chemical monitoring effort, to develop a biological component which will complement and assist continuing chemical monitoring in its ability to detect contaminants originating from oil sands plants; and also to assess the effects of these contaminants on aquatic ecosystems.

2. PHASE 1: ESTABLISHMENT OF BASELINE CONDITIONS

The first five years of AOSERP were dedicated solely to the Athabasca deposit. Beginning in 1979 some preliminary work began in the Cold Lake deposit, however it has been limited to groundwater related projects. The present discussion is therefore limited to the Athabasca deposit.

2.1 Surface Water Research in the Athabasca Deposit Region

Surface water monitoring and research for AOSERP has been largely directed to needs identified by life scientists, particularly fisheries researchers. Contaminant transport has also been an issue, particularly transport of contaminants beyond Alberta's boundaries.

2.1.1 Water Quantity

A framework for hydrotechnical studies was proposed by the Conservation and Utilization Committee of the Natural Resources Coordinating Council before the inception of the Program (Thiessen, 1974). Table 3 shows the locations recommended by the Committee for guaging stations. The "$" symbol indicates the stations that were operational at the time of writing. In addition, stations were established on Hartley Creek near Fort MacKay, Joslyn Creek near Fort MacKay, Richardson River near its mouth in the Athabasca Delta and an Unnamed Creek near Fort McKay. A station was also established on Gregoire Lake, southeast of Fort McMurray.

At present, the network consists of eighteen permanant recording guages maintained by the Water Survey of Canada under a federal/provincial agreement with the Technical Services Division of Alberta Environment (Figure 3). At various times in the past, gauges have operated at other locations for short periods, notably the Natural Resources Coordinating Council recommended locations at Horse River, Tar River and Asphalt Creek. Temporary guages were also operated on three lakes on the Birch Mountain Plateau and at the headwaters of the Ells River.

Table 3
Baseline Network of
Alberta Oil Sands Hydrometric Stations

Stream	Hydrometric Station Location	Station No.	Drainage Area Above Station (sq. mi.)	Years of Stream Flow
$Athabasca River	below McMurray	7DA1	50,000	1957 - present
$Athabasca River	Embarras Airport		58,700	1959 - 1971 stage only 1971 - present
*Horse River	near the mouth	7CC1	850	1930 - 31 only
$Hangingstone River	near the mouth	7CD4	344	1965 - present
$Clearwater River	Draper	7CD1	11,800	1957 - present
$Clearwater River	above Christina River	7CD5	6,520	1966 - present
West of Athabasca River				
$Poplar Creek	near the mouth	7DA7	100	1972 - present
Beaver River	near the mouth	7DA5	195	1972 - present
$*Beaver River	above Syncrude Dam			none
$MacKay River	near the mouth	7DB1	2,490	1972 - present
*Dunkirk	near the mouth			none
*Dover	near the mouth			none
$*Ellis River	near the mouth		1,080	none
*Ellis River	below Gardiner Lake			none
$*Joslyn Creek	near the mouth			none
*Tar River	near the mouth		133	none
*Calumet River	near the mouth		76	none
*Pierre River	near the mouth		63	none
*Asphalt Creek	near the mouth		120	none
$*Creek north of Asphalt Creek	near the mouth		137	none
East of Athabasca River				
$Steepbank River	near the mouth	7DA6	573	1972 - present
$*Muskeg River	near the mouth		571	1973 - present
	above Hartley Creek			none
$Firebag River	10 miles above mouth	7CD1	2,300	1972 - present

*Station to be installed as part of the network
$Station currently active, March, 1982

Source: Thiessen (1974)

The basins chosen for long term gauging are representative of the geomorphic types present in the region or which were considered likely to be developed in the near future. (Yaremko and Murray, 1979). Data for at least three years were obtained for an additional 15 locations, to establish a basis for comparison with the long term monitoring stations and to provide discharge data for baseline water quality studies throughout the region. Full year precipitation data is available from McMurray Airport, Embarras Airport, Fort Chipewyan Airport, Thickwood Hills Fire Tower and the AOSERP Mildred Lake Research Facility.

Also shown on figure 3 are the locations of snow courses that have been maintained by AOSERP since 1976. An additional, denser set of measurements are made in the vicinity of the operating Oil Sands upgrading plants (figure 4) for water chemistry purposes, which includes snow depth and maturity parameters.

2.1.1 Design Storm Analysis

There are three airport meterological stations in the region with a sufficiently long period of record for reasonable calculation of design storms. These are located at Fort McMurray, Embarras and Fort Chipewyan. MAPS stations are located at Stony Mountain, Thickwood River and Mildred Lake. Records from Stony Mountain and Thickwood begin in 1957 and from Mildred Lake in 1973. Summer data is available from fifteen Alberta Forest Service lookouts which are scattered throughout the region (figure 3).

The rain gauge density in the region is so low, particularly in the critical pre-breakup and early spring periods that it is difficult to predict a value for the Maximum Probable Precipitation (MPP). In view of the very large water retaining structures in the area (in particular the tar sand upgrading plant tailings ponds), and the environmental consequences of a dyke failure, the MPP is of considerable interest to mining engineering.

Verschuren and Wojtiw (1980) have carried out a storm/station density analysis for the region and found it to be subject to an unusually high incidence of severe storms. A "Severe Storm" being defined as one producing a maximum depth of precipitation in excess of 150 mm. They also determined that there is a high degree of variability in the incidence of storms and that they tend to track from northwest to southeast through the region. depth-area curves for the Athabasca basin as a whole were published in the same report for a maximized 24 hour probable maximum precipitation storm, and Depth-Area Distribution (DAD) curves for 6, 12, 24, 48, and 96 hour storms. DAD curve envelopes for June, July, August, and September are also presented. These families of curves are considered reliable and useful for storms in excess of 1000 Km^2 in area.

The smaller, 100 to 1000 Km^2 convective summer storms are commonly observed in the area, particularly when forest fires are burning nearby.

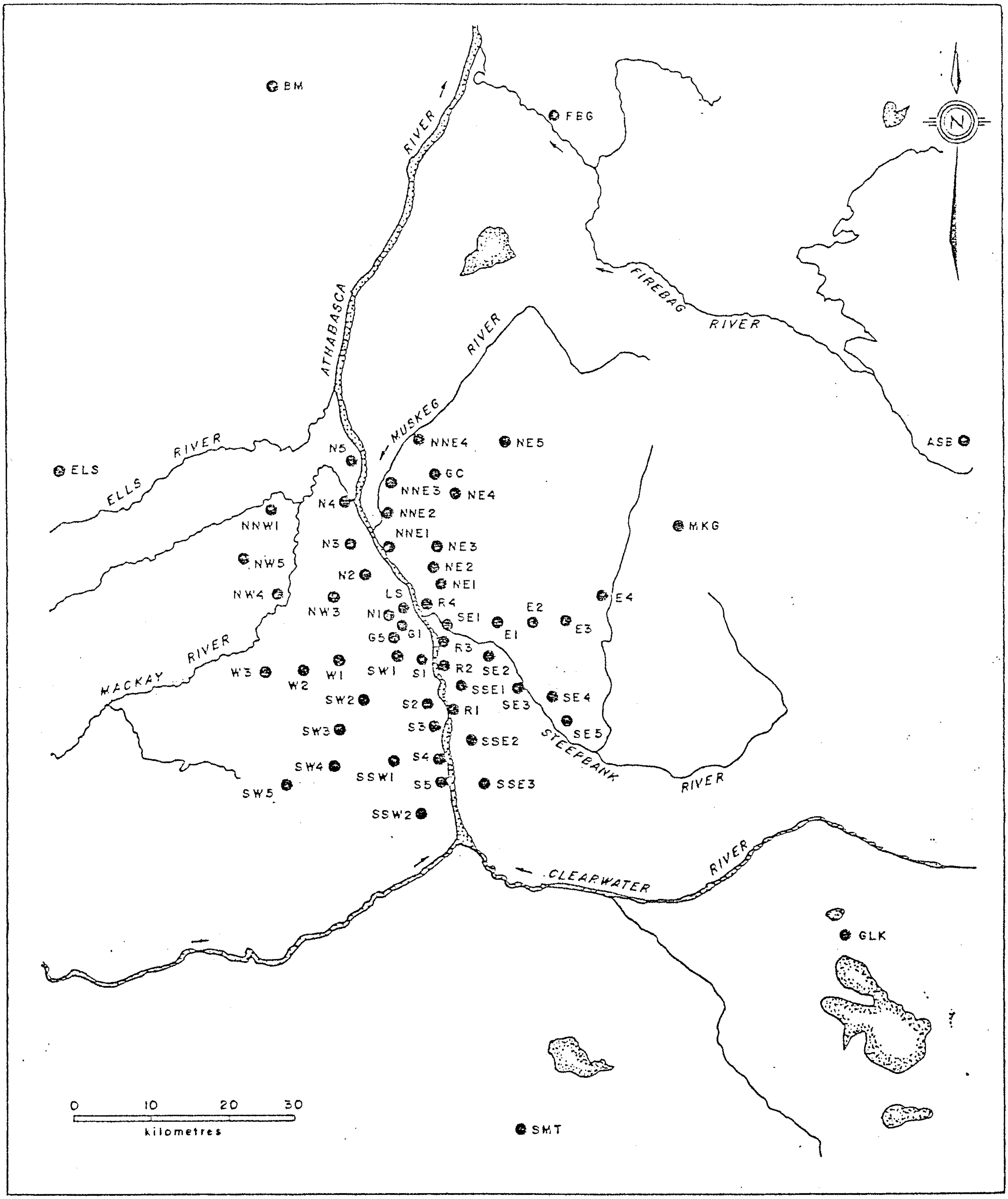

FIG. 4 MAP OF THE STUDY AREA. DOTS MARK THE LOCATIONS AT WHICH SNOW WAS SAMPLED.

SOURCE: MURRAY (1981)

Virtually no data is available on the intensity of precipitation from the storms which seem to track between McMurray and Embarras around the Birch Mountains from northwest to southeast.

Weather radar would be the most practical approach to obtaining data on these storms, however, to date, this has not been done by Alberta Environment.

Longley and Janz (1978) have computed short-duration rainfall-intensity tables for Fort McMurray (Table 1) which will generally serve for the design of small structures.

2.1.2 Extreme flow analysis

Both flooding and drought conditions are of environmental and economic interest in the Athabasca Oil Sands region. A preliminary assessment of both high and low flows was done by Neill and Evans (1979) using a mean flood/mean low flow coefficient technique which relates mean annual flood to the area of a catchment in the form:

$$C = \frac{Qm}{A^{0.8}}$$

where C = flood coefficient
Qm = mean annual flood
A = catchment area

for maximum flows and in the form:

$$Cmin = \frac{Qmin}{A}$$

where Cmin = minimum flow coefficient
Qmin = mean mimimum discharge
A = catchment area

for minimum flows. Their results are shown in tables 4 and 5.

Neill and Evans also attempted an extreme flood analysis using a scaled up unit hydrograph method for the Hangingstone and MacKay basins, but data was judged to be too sparse for a rigourous treatment.

Gerard (1981) has carried out a regional spatial and temporal analysis of low flows that suggests some important interrelationships amongst surface water, groundwater and temperature need to be worked out. In particular, he found that two low flow periods in this region. The first occurs at freeze-up when ice cover formation increases flow resistance and stage increases to accomodate the accompanying excess of mass, thus reducing discharge. The second occurs in late winter when storage in the basin has been depleted. The freeze up discharge sag is accentuated in small streams by ice abstraction. Gerard believes that the late winter or "true" flow minimum discharge is spatially affected by three catchment parameters: unfrozed stream length, area of lakes and surficial geology. These features are considered more important than gross catchment area.

Table 4. Maximum flows.
Source: Neill and Evans (1979)

River	Drainage Area (A) Km^2	No. of years of Record	Mean Annual Flood (Qm) m^3/s	Flood Coefft $Qm/A^{0.8}$	Maximum Recorded m^3/s	Estimated 20-Year Flood m^3/s	Ratio 20-Year to Mean
Athabasca (below Fort McMurray)	133 000	20	2720	0.22	4786	4430	1.63
Clearwater	30 600	19	520	0.13	728	860	1.65
Poplar Ck.	151	5	7.8	0.14	17.8	17.5	2.2
MacKay	5 230	5	190	0.20	306	740[a]	3.9[a]
Steepbank	1 373	4	38	0.12	62	(95)	(2.5)[b]
Muskeg	1 456	4	26	0.08	43	(65)	(2.5)
Firebag	6 035	3	78[c]	0.07	99	(195)	(2.5)
Hangingstone	914	13	57[c]	0.24	135	140	2.5

[a] Figure considered too high, because 5-year sample is probably unrepresentative.
[b] Bracketed figures are based on assumed ratios to mean flood.
[c] Daily value: all others are instantaneous maxima.

Table 5. Minimum flows.

River	Drainage Area (A) km^2	No. of Years	Mean Annual Min. (Qmin) m^3/s	Minimum Coefficient $=\frac{Qmin}{A}$ $m^3/s/km^2$	Minimum Recorded Daily m^3/s	Est'd 20-Year Minimum m^3/s	Minimum Recorded Monthly m^3/s	Date
Stations listed in Table 4 (Maximum flows)								
Athabasca (Below Fort McMurray)	133 000	18	138	0.0010	104	95	111	Feb. 59
Clearwater	30 600	19	44	0.0014	30	30	33.4	Feb. 58
Poplar Ck.	151	5	0	0	0	0	0	Jan.-Mar. 76
Mackay	5 230	5	0.29	0.00005	0.02	0	0.10	Feb. 73
Steepbank	1 373	4	0.38	0.0027	0.25	-	0.30	Dec. 77
Muskeg	1 456	4	0.21	0.00014	0.17	-	0.21	Dec. 76
Firebag	6 035	6	7.0	0.0013	7.1	5.6	7.08	Feb. 72
Hangingstone	914	9	0.20	0.00022	0	0	0.09	Feb. 75
Other Stations								
Beaver (Above Syncrude)	176	2			0		0	(Feb.)
Dunkirk	1 580	2			0.03		0.03	Jan. 76
Thickwood	170	1			0		0.006	Mar. 77
Upper Ells	1 365	2			0.20		0.21	Mar. 77
Lower Ells	2 480	2			0.40		0.64	Mar. 77
Joslyn	248	2			0.003		0.009	Dec. 77
Upper Tar	97	1			0		0	(Feb.-Mar.)
Calumet	181	2			0		0	(Feb.)
Pierre	130	2			0		0	(Feb.-Mar.)
Asphalt	149	2			0		0	(Feb.-Mar.)
Unnamed	280	2			0.03		0.03	Dec. 76
Hartley	368	2			0.008		0.007	Jan. 77
Horse	2 180	2			0.34		0.42	Jan. 76

In general, stream length and catchment area are correlated, however when smaller tributaries are frozen to the bed they are not contributing to the discharge in the principal stream. Therefore, only the unfrozen stream length is relevant.

Large lakes receive groundwater discharge throughout the winter through their unfrozen beds and thus contribute significantly to baseflow in their basins.

Surficial geology is also a significant factor in that low permeability materials (clay, very fine silt and tar sand) will inhibit groundwater discharge to unfrozen stream and lake beds, while highly permeable materials (gravel, sand and coarse silt) will facilitate groundwater discharge.

Gerard stratified the data by surficial geology type and related discharge to the area of lakes and unfrozen stream length using the following empirical equation:

$$Q = al^b + CL$$

where
Q = discharge
l = unfrozen stream length
L = area of lakes
a,b,c = regression coefficients.

His data are shown in table 6. He then derived the following regression equations:

$$Q = 0.91\ l^{1.5} + 13.6\ L$$ (High permeability surficial deposits, $r = 0.85$)

$$Q = 8.9\ l^{1.7} + 9.0\ L$$ (Low permeability surficial deposits, $r = 0.99$)

If it is assumed $b = 1.0$, then a and c become 9.4 and 12.7 for high permeability terrain and 2.0 and 9.3 for low permeability terrain. Not unexpectedly, coarse grained terrain yields about 5 times the low flow discharge observed in low permeability terrains.

Since large lakes are not common in the region, Gerard concluded the difference in coefficients between the two terrain types is probably not significant. A possible challenge to this assertion might be the absence of a term for muskeg storage since much of the region is peatland. Schwartz (1979, 1980) has shown peat to be a major reservoir, however, geochemical data suggests it is not a significant factor during the late winter low flow period. In fact, the same data shows the sole source of surface water to be glacial drift-derived groundwater in late winter.

The writer has confirmed Gerard's technique for the 1982 low flow period for the stream indicated in table 6. Data were derived from field observations made March 24, 1982 by the writer and Water Survey of Canada personnel between March 23 and March 28, 1982. The only major discrepencies occur with the Ells River data. It is possible an ice jam has occurred upstream from the WSC gauge, as open water was observed in the headwaters of the catchment.

Table 6. Catchment parameters and minimum flows, 1976 and 1982 Source: Gerard (1981)
1982 data; this report

Catchment	Area (km^2)	Stream length (km) 1976	Stream length (km) 1982	Lake area (km^2)	Surface Geology	Minimum Discharge 1976 (L/s)	Minimum Discharge (L/s) 1982 Est.	Minimum Discharge (L/s) 1982 Actual
Birch R.	10000	810		15	Silt/clay	1220		
Dover R.	955	88		3.8	"	195		
Dunkirk R.	1580	133		2.0	"	28		
Ells R. at Gardner Lk.	1360	85	40	120	"	1300	1141	36
Ells R.	2490	236		120	"	1390		
Hangingstone R.	890	81	62	0.4	"	184	86	286
Horse R.	1220	193		0.5	"	337		
Mackay R.	5410	376		5.8	"	433		
Dover R. *	--	63		3.8	"	180 (±20%)		
MacKay R. *	--	290		2.0	"	160 (±20%)		
Steepbank R.	1350	107		0	Silt/sand	400		
Clearwater R.	30500	2370		900	Sand	52400		
Firebag R.	6032	382		17.6	"	8490		
Hartley Ck.	368	10	14	0	"	22	12	5
Muskeg R.	1450	71		5.0	"	430		
Richardson R.	2950	268		12.0	"	10100		
Upper Steepbank R. *	305	31	40	0	Sand/silt	120 (±50%)	220	225
Firebag trib. #1 *	380	20		0.3	Sand	50 (±50%)		
Firebag trib. #2 *	290	10		0	"	50 (±40%)		
Kearl Ck. *	385	8		5.0	"	90 (±20%)		
Muskeg R. *	540	35	35	0	"	140 (±30%)	179	147
Unnamed Ck.	280	10		0.75	"			
Joselyn Ck.			16				32	3

* Measurements by Alberta Research Council, 26 and 27 February, 1976.

2.1.3 Water Balance and Annual Flows

Neill and Evans (1979) have proposed a mean annual streamflow balance for the region (figure 5) and have calculated that local tributaries contribute from 5% to 16% of the discharge into Lake Athabasca over a 100 year period. Clearly, the bulk of the water passing through the regin has a source in another area.

The principal outside sources are the Athabasca River upstream from McMurray (72% of Lake Athabasca inflow), and the Clearwater River (18.0%). On an annual basis Neill and Evans claim the flows in the Athabasca and the Clearwater are uncorrelated, reflecting the very different nature of the two catchments. The Athabasca rises in the

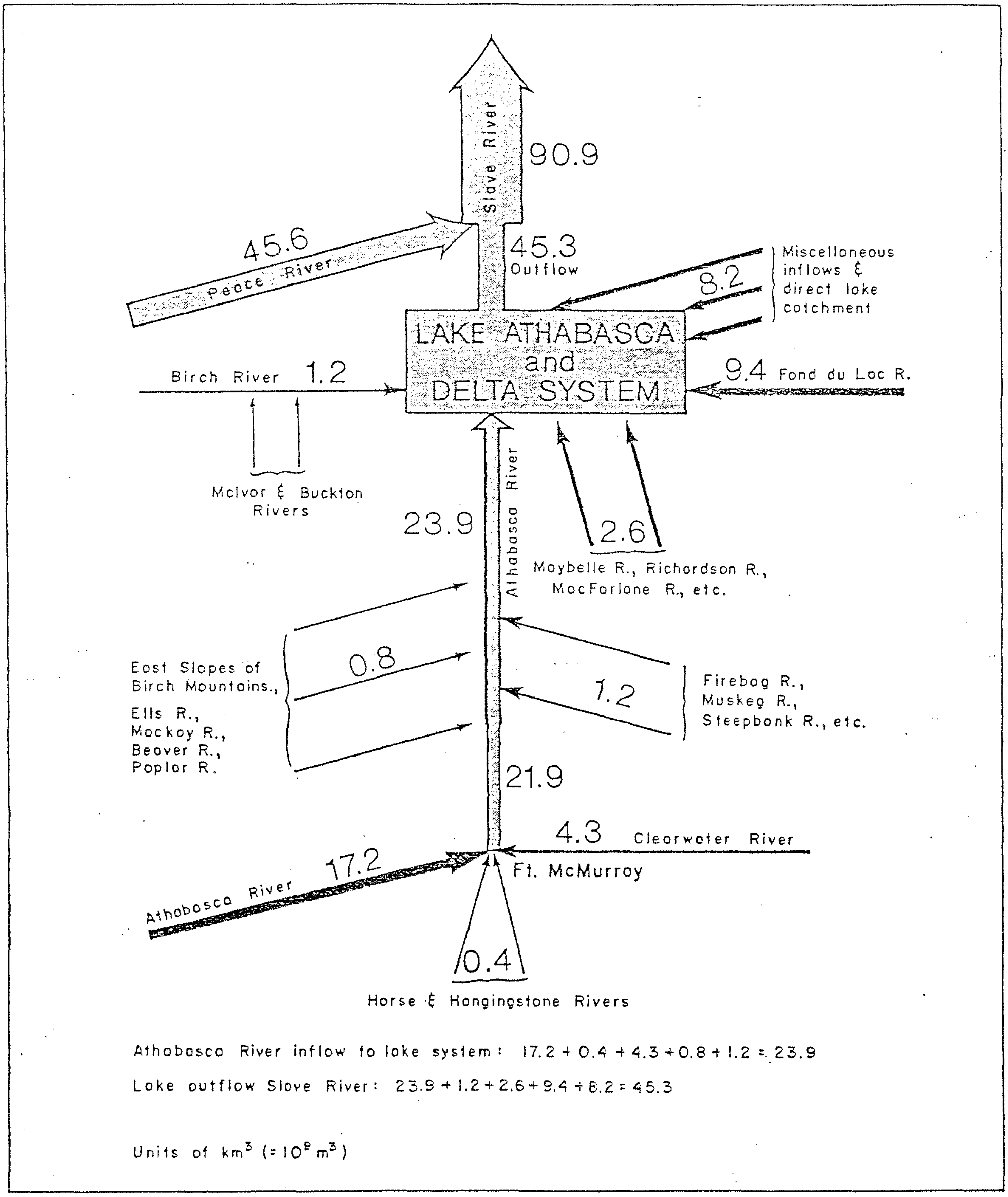

FIG. 5 MEAN ANNUAL STREAMFLOW BALANCE

(After Neill and Evans, 1979)

Rocky Mountains at Columbia Icefields whereas the Clearwater is a shield stream. Consequently flows in the Athabasca are more variable from year to year (28% versus 22% for the Clearwater) possess a wider range for minimum annual discharge to maximum (19:1 for the Athabasca compared to 6:1 for the Clearwater). Thus most of the volume and much of the variability in flows in the mainstem Athabasca downstream from McMurray should be explainable by hydrological conditions outside the Athabasca Oil Sands region, under a state of nature.

Water balance analyses for the region periods shorter than a year are reported by Neill and Evans to be unreliable in that discharge measurements made at the Embarras gauge, at the head of the Athabasca Delta, often do not check with inflows at McMurray and from the local tributaries (table 7).

Long term, whole year precipitation data is available for the region only at Fort McMurray and Fort Chipewyan. The fragmentary short term data that is available indicates considerable spatial variation in snowpack (table 2) and, as discussed above, in summer rainfall. Recent snowpack data (Murray, 1981) confirm this finding.

Evapotranspiration data is also lacking, although a short evaporation pan record is available at Mildred Lake. Given the short streamflow records in the local tributaries, the inconsistencies in gauge data on the mainstem Athabasca, and the lack of evapotranspiration data, reliable water balance modelling is not possible. Neill and Evans attempted to model the Beaver River basin using climatic data, but concluded that data limitations made regional scale modelling unsatisfactory.

Neill and Evans also carried out a regional analysis of variability in runoff for 1976 and 1977, the two years when the whole region was extensively gauged. They found that the streams on the southern and eastern sides of the Athabasca region yielded the greatest average annual depth of runoff. They also found that the spatial variability in precipitation only partly explained this phenomenon. The runoff coefficients thus derived (table 8) show a mean value fo 0.14 (S=0.04, N=7) West of the Athabasca, 0.21 (S=0.08, N=3) East of the Athabasca and 0.27 (S=0.05, N=2) south of Fort McMurray.

Annual variability in flows in the mainstem Athabasca, Clearwater and principal local tributaries is shown in table 9.

Table 7: Comparison of reported annual flows in Athabasca River at Fort McMurray and Embarras.

Year	Fort McMurray	Annual Flow Volumes in km^3 Embarras	Difference	Tributary Gauged Inflows Between
1972	23.2	23.7	0.5	
1973	23.3	25.6	2.3	
1974	(26.6)	incomplete data		
1975	21.6	24.9	3.3	
1976	21.45	21.70	0.25	1.63
1977	24.17	23.55	-0.62	1.26
5-year average	22.7	23.9	1.2	

Notes

1. Gauged tributary inflows are tabulated for 1976 and 1977 only, because a large part of the inflow was not gauged prior to 1976.
2. Gauged tributary inflow reported for 1976 and 1977 represents approximately 80% of the tributary drainage area between Fort McMurray and Embarras.

Table 8: Spatial variation of runoff coefficients over the study area, 1976 to 1977.

Basin	2-Year Runoff (total) mm	2-Year Estimated Precipitation mm	Runoff Coefficient = Runoff/ Precipitation
West of Athabasca River			
Upper Beaver & Poplar	188	1000	0.19
Dunkirk	110	800	0.14
MacKay (less Dunkirk)	130	770	0.17
Upper Ells	160	870	0.18
Lower Ells	77	750	0.10
Joslyn & Tar	112	810	0.14
Calumet & Pierre & Asphalt & Unnamed	74	890	0.08
East of Athabasca River			
Steepbank	180	820	0.22
Muskeg	95	770	0.12
Firebag	230	820[a]	0.28[a]
South of Fort McMurray			
Horse	240	1030	0.23
Hangingstone	323	1090	0.30

[a] Precipitation not well defined.

Table 9: Year to year variability of selected monthly flows.

Month and River	No. of Years	Mean Monthly Flow* m^3/s	Standard Deviation % of Mean	Recorded High approx. % of Mean	Recorded Low approx. % of Mean
March (low flows)					
Athabasca	20	168	18%	135%	70%
MacKay	5	0.4	-	160%	40%
Steepbank	4	0.5	-	120%	85%
Muskeg	4	0.4	-	110%	85%
Hangingstone	8	0.35	32%	130%	40%
Clearwater	20	52	16%	135%	75%
May (high flows)					
Steepbank	4	13	-	195%	45%
Muskeg	4	8	-	250%	30%
Hangingstone	13	11	55%	180%	17%
Clearwater	20	263	33%	140%	50%
June (high flows)					
Athabasca	20	1375	25%	140%	60%
MacKay	5	47	-	335%	20%
October (Intermediate flows)					
Athabasca	21	607	24%	140%	60%
MacKay	6	13	-	200%	25%
Steepbank	5	7	-	240%	35%
Muskeg	4	6	-	195%	55%
Hangingstone	13	4.7	50%	165%	45%
Clearwater	21	144	39%	170%	50%

* Average flow for the month, averaged again over the number of years listed in column 2.

SOURCE: Tables 7 through 9 Neill and Evans (1979)

2.1.2 Water Quality

Water pollution is a prime environmental issue. Consequently, the Natural Resources Coordination Council recommended collection of water quality begin while the region was relatively undisturbed to establish background conditions (Thiessen, 1974). AOSERP began collecting data on inorganic water quality at its inception and the Water Quality Branch of the Pollution Control Division is carrying on a routine monitoring program to the present. Thus, a reasonably dependable time series data base is available for interpretive and Clean Water Act enforcement purposes.

A parallel data set for suspended sediment discharge has been carried on by Water Survey of Canada in conjunction with the hydrometric network described elsewhere.

The distribution and sedimentation pattern of man-made and natural contaminants is of considerable interest to environmental science. The location, nature and extent of sources of man made contaminants in the Athabasca system below McMurray is well known (Strosher and Peake, 1976). Since little is introduced into the system by the bitumen upgrading process that is not present naturally, man's activity can only be discerned by the enrichment of surface waters, groundwaters and sediments with particular contaminants. The main concerns are for increased suspended sediment loadings, depressurization waters, toxic organic substances and heavy metals.

Baseline studies by Allan and Jackson (1978) showed the heavy metals to be low in concentration compared with other natural waters. (table 10). Concentrations in sediment tended to increase with distance downstream from McMurray and peaked in the Athabasca Delta in Lake Athabasca. Vanadium and nickel were strongly correlated with organic carbon and appear to be naturally present in an organic form, most commonly associated with clays and silty clay. Concentrations from 66 mg/L to 121 mg/L have been reported from the Athabasca River and Delta, respectively.

Vanadium is known to be toxic to fish in the ionized form. Concentrations of 40 mg/L in a neutral pH environment have been shown to be lethal to trout (Giles et al, 1979), thus any mobilization of vanadium from sediments could pose significant environmental hazards. Vanadium is the most abundant metal in upgrading plant effluent, where concentrations ranging from 0.25 to 0.6 mg/L are found. Background vanadium ion concentrations in the Athabasca River are at the detection level (0.004 mg/L) according to Strosher and Peake (1976) and Andreychuk (1980). Vanadium is not commonly included in water quality analyses, however what little is available tends to confirm the 10^{-3} background figure (Akena and Christian, 1981).

Sediment loadings are normally high in the Athabasca during the open water season, however the bulk is discharged during June or July in most years (Neill et al, 1981). In the tributaries, the sediment discharge peak occurs in the mid-April to early May period.

A normal peak discharge sediment concentration would be in the order of 500 mg/L. Recession limb concentrations are around 100 to 200 mg/L in the mainstem. The tributary loadings are relatively minor, with peak loadings around 20 to 50 mg/L and recession limb loadings of around 10 mg/L. Peak discharge concentrations of 500 to 1000 mg/L have been reported on the Ells, McKay and Poplar Rivers, however (Warner and Spitzer, 1979).

Comparison of mean vanadium concentrations in the mainstem Athabasca River system with other North American Sites. (Source: Allan and Jackson, 1978).

Suspended sediment concentrations in excess of 100 mg/L in natural streams have been shown to result in reduced species diversity amongst aquatic biota if sustained for a long time. It has also been shown that natural communities can recover from unusually large concentrations, short duration transient events within a single season. Reaches subject to chronically large rates of sedimentation by fine material tend to have low biological productivity, according to Griffiths and Walton (1978).

Mine depressurization waters are normally derived from the D-2 zone or the so called "water sands" below the McMurray formation. The Water Sands have very poor quality groundwater and may be expected to possess 10,000 mg/L TDS over much of the area (5,000 mg/L TDS in the northwest) according to Hackbarth and Nastasa (1979). Giles et al (1979) found 20% to 35% of these levels to be toxic to native fish in a 10 day LC_{50} test.

Apart from low levels of agricultural pesticide residue derived from sources outside the region, background organic material in the Athabasca River can be grouped into five major components:

1) Water soluable constituents
2) Toxins and lignans
3) Asphaltenes
4) Polar constituents
5) Hydrocarbons

Wastewaters from the upgrading process contain six orders of magnitude higher concentrations of these substances (tabl[illegible] general groups of organic compounds are not [illegible] toxic. They do, however, provi[illegible] probable concentrations of phen[illegible] highly toxic compounds and very [illegible]

There is some evidence that [illegible] more toxic in combination than e[illegible] et al (1979), although in all cas[illegible] test organisms (rainbow trout) was les[illegible] by theory. In all cases, the toxic doses were three [illegible] of magnitude greater than have been observed either in the Athabasca River system or in oil sands upgrading plant effluents.

It can be seen from the foregoing that unless a substantial degree of concentration of contaminants occurs, the oil sands plants are unlikely to have a significant impact on the Athabasca River system insofar as heavy metals is concerned. Concentration of contaminants could occur naturally by the normal mixing and sedimentation patterns of the river; which is demonstrably occuring in a number of reaches and the Athabasca Delta in Lake Athabasca, or by system failures in the oil sands plants.

The latter case can be detected fairly readily by inspection and effluent monitoring. The former phenomena require scientific research. Mixing patterns in the Athabasca River, Delta and Lake Athabasca have been studied by Beltaos (1978a, 1978b, 1979); Lipsett and Beltaos (1978); Neill et al (1981) and Harrington (in preparation).

Table 11: Organic constituents extracted from waters and sediments.

Sample	Number	Asphal-tenes	Aliphatic Hydrocarbons	Aromatic Hydrocarbons	Polar Compounds
Waters (in mg/l)					
Coke Storage Runoff		2.7	0.03	0.05	0.08
Syncrude Mine Waters	1	3.4	0.11	0.06	0.03
	2	1.8	0.01	0.02	0.02
GCOS Upgrading Plant Effluent	1	1.3	0.33	0.19	0.10
	2	1.9	3.00	1.27	0.74
	3	2.0	1.62	0.97	0.13
Athabasca River Upstream	1	-	0.004	0.009	0.030
	2	-	0.001	0.002	0.010
	3	-	0.001	0.001	0.002
Athabasca River Downstream	1	-	0.006	0.006	0.030
	2	-	0.001	0.001	0.010
	3	-	0.024	0.016	0.003
Sediments (mg/kg of dry sediment)					
Athabasca Sediment Upstream	1	301	33.5	11.9	9.0
	2	204	24.1	9.7	4.1
	3	77	19.5	6.6	2.3
Athabasca Sediment Downstream	1	437	54.5	38.3	11.9
	2	236	50.9	36.2	2.2
	3	171	24.6	21.6	2.2

SOURCE: Strosher and Peake (1978)

These studies have been largely theoretical in their approach, and while they have been successful in predicting neutral dye concentrations at a point downstream from a source, they have not been used to map the mixing characteristics of the region in a systematic way, except for sedimentation and mixing patterns in the western basin of Lake Athabasca.

The western basin of Lake Athabasca appears to act like a reach of the Athabasca River. Four plane jets form at the mouths of the distributary channels in the delta and these dictate the sedimentation pattern along the delta front and the distribution of flow velocities within the lake proper. The flow velocities in turn dictate the pattern of mixing between shield-derived water and Athabasca River water. The process is extensively modified by winds and by outlet conditions. The Coriolus effect also modifies the pattern, however the degree of modification remains to be assessed (Neill et al, 1981).

Sedimentation patterns within the mainstem of the Athabasca have been mapped by the Alberta Research Council (Doyle, 1977), but the implications of the patterns have not yet been explored from a contaminant transport and deposition viewpoint.

2.2 GROUNDWATER

Groundwater investigations were also proposed for the Athabasca Oil Sands region to the Natural Resources Co-ordinating Council before the inception of AOSERP (Thiessen, 1974). At about the same time, the same environmental concerns were raised by the Oil Sands Environmental Study Group (OSESG) together with a second category of geotechnical problems related to mine wall stability and de-watering which are also related to groundwater (Gorrell, 1974).

In response to these data needs and in parallel with the surface water gauging effort a network of groundwater monitoring stations was established and maintained by the Alberta Research Council Groundwater Department (ARC) with financial support from Alberta Energy and Natural Resources and logistic support from AOSERP (Hackbarth, ed. 1976). The ARC Groundwater Department has also carried out reconnaisance scale mapping of the groundwater resources of the region. Ozoray (1974) mapped the southern region while Ozoray, Hackbarth and Lytviak (1978) mapped the northern part. Hackbarth and Nastasa (1979) carried out a regional synthesis of all available data. A detailed study of the Muskeg River Basin was carried out for AOSERP by Schwartz (1979, 1980).

Several phenomena reported by the ARC hydrogeologists are of particular importance to AOSERP. First, Ozoray (1974) reported cold mineral springs along the Clearwater and Athabasca rivers which are rich in chlorides and typically smell of hydrogen sulphide. They produce calcareous tufa deposits where they surface. Second, Ozoray (1974) proposed the concept of "quasi-springs" as a groundwater discharge area of considerable extent which gives rise to a muskeg bog which in turn acts as a source for a surface stream. He suggested these features are the product of a combination of climafrost, discontinuous permafrost and a generally flat upland topography with a gentle slope. Waters from these features are chemically characterised as bicarbonate with various cations and lower total dissolved solids than other groundwaters.

Ozoray et al (1978) continued this work northward to Bitumount and described more karst phenomena, including the Saline Spring ("Le Grand Saline") near Mildred Lake on the east bank of the Athabasca.

Hackbarth and Nastasa (1979) identified hydrostratigraphic units in the region on the basis of pressure head observations and water chemistry from a network of seventy-five observation wells. These wells and the data derived from them are described in Hackbarth, ed. (1976). The hydrostratigraphic units are:

1) The "K-Q", comprising a vertical hydraulic gradient, cold, fresh, Sodium-magnesium bicarbonate water found in the cretaceous bedrock and the quaternary drift.

2) The "D-2" unit which is characterized by lower hydraulic head than in the overlying McMurray formation, largely horizontal hydraulic gradients (ie. groundwater flow is parallel to bedding), and warmer, saltier water than is found in the K-Q unit.

3) The "D-1" unit shows piezometric heads that corresponds to the land surface elevation and extremely high (5×10^5 mg/L) concentrations of salts which are dominantly chlorides.

The D-2 and D-1 units are separated by the Elk Point/Prairie Evaporites, a thick sequence of anhydrite and gypsum that acts as an aquitard wherever present and results solution collapse features in the overlying D-1 rock units wherever it is absent.

K-Q permeabilities are intergranular and in the order of 10^{-3} to 10^{-4} cm/s. Intergranular permeabilities in the D-2 and D-1 are very small (10^{-6} to 10^{-7} cm/s) and thus most of the groundwater flow must be by fracture permeability. Babcock (1975) mapped fracture orientation and style in the McMurray (K-Q unit) and Waterways (D-2 unit) which lends support to Hackbarth and Nastasa's hypothesis that D-2 waters are leakage from the K-Q unit. Babcock shows the major joint set orientation in the waterways as being oriented northwest to southeast, which appears to be at odds with Hackbarth and Nastasa's contention that the general orientation of the groundwater flow is to the northeast. (There is sufficient scatter in Babcock's data to allow a general trend of flow along a minor joint set to the northeast, however).

Schwartz (1979, 1980) supported Ozoray's "quasi-spring" concept to some extent by showing that baseflow in the Muskeg River basin is largely derived from groundwater discharged from the Pleistocene drift (Hackbarth and Nastasa's "K-Q" unit). He also suggested that water in some of the Muskeg bogs themselves may have a source in deeper flow systems. His data tables show a slight increase in Cl- and SO^{2-}_4 concentrations with depth beneath the Muskeg, although the concentrations are two orders of magnitude below D-2 average concentrations. The prime environmental concerns that arise from groundwater flow disruption from industrial activity are:

1) The potential for mixing D-1 and K-Q unit waters and the consequent ecological impact when these saline waters reach surface streams.

2) The direct discharge of D-1 waters; to surface streams and consequent degradation of surface waters.

3) The impact of dewatering and muskeg removal on groundwater recharge to the K-Q and D-1 hydrostratigraphic units and surface stream baseflow, particularly in the low flow period.

4) The ecological impact of reduced low flows in surface streams resulting from the disruption of groundwater flow systems.

3. PHASE II: EVALUATION OF HAZARDS TO THE AQUATIC ENVIRONMENT FROM MEGA PROJECTS

Large scale industrial activity and rapid urbanization in the Athabasca oil sands region will and has radically altered the environment of the region. Some of these influences are immediately obvious, such as a high level of air pollution in a previously pristine area and the rapid growth of Fort McMurray. Others are subtle, such as the change in growth rate of the Athabasca Delta and the diversity of biotic species in the Athabasca River and its tributaries. The second phase of AOSERP is directed toward predicting the effects of industrialization at a regional scale to assist policy makers with regulation of the phenomenon and proposing mitigative measures to soften its effects on the people, flora and fauna of the region.

3.1.1 Levels and Flows

Sufficient historical flow data now exists to carry out some first approximation predictive modelling, particularly with respect to low flow, sediment discharge and mixing. Hudson (in preparation) reports elsewhere in this volume on a small basin study he is conducting to assess the effects of muskeg removal operations on sediment and water discharge hydrographs. The results from this study will be combined with the results from previous and parallel studies into aquatic biology to determine quantitatively what changes may be expected. Further, since sediment and water hydrographs may be expected to peak higher and sooner and sediment hydrographs will have a broader peak, Hudson's model may be used as input to a mainstem mixing model as a transient source.

Harrington (in preparation) is acquiring data to establish boundary conditions and to validate a mixing model for Lake Athabasca. For the first time the consequences of variation in the sediment discharge hydrograph for the Athabasca River on Lake Athabasca will be estimated with defined reliability. Future work should be oriented toward extending the model through the Athabasca Delta and each reach of the Athabasca River.

Estimation of low flows is an important element in assessing the effects of pollutants on the ecosystems of the tributary streams. The procedure proposed by Gerard (1981) appears to work on some streams and not on others. In particular, mapping groundwater discharge zones and springs should have some priority. String bogs may prove to be of considerable hydrologic significance to low flow estimation if Ozoray's (1974) interpretation is correct. This should be tested, and if possible, modelled. The linkage between discontinuous permafrost and regional hydrology has not been addressed at all and should now be pursued.

Preliminary time series analysis of annual precipitation depth data and stream flow records for those streams with five or more years of record have been carried out by the writer. Spectra computed from such a short period of record are not too reliable, however several patterns have emerged.

Those tributaries with significant lake or muskeg storage possess monochromatic spectra which do not suggest any periodic events. Only random events (those with zero period) and annual cycles appear.

The second group tend to mimic the spectra for annual precipitation at McMurray airport. A recurring 2 to 4 year period event appears on these records and the phase spectra show similar phase shift patterns. Of the five streams in the second group, three (including the Athabasca River) show a phase shift pattern which closely resembles the precipitation record. The Clearwater River event spectrum is essentially the same as the Athabasca River (except that it shows a three year recurring flood/drought cycle instead of a four year), however the phase spectra are reversed. The fifth stream, the MacKay River, has no phase shift. Gerard (1981) published an "eyeball cross-correlation" between summer precipitation at McMurray airport and mimimum discharge in the Hangingstone River. The two time series track very closely, except they display a three year delay. Comparison of event spectra for the same two series shows a very close similarity. The main difference between the two is the pronounced three year peak in the Hangingstone discharge record and a more subdued three to four year peak in the precipitation record.

The physical significance of these spectral patterns and the three year delay demonstrated by Gerard merits further study.

3.1.2 Water Quality

The linkages amongst groundwater discharge, hydrology, river mechanics and water chemistry remain to be more fully explored. Once these linkages have been worked out, it will be possible to characterize background water chemistry with sufficient confidence to adequately assess the regional environmental impact of the synthetic fuel industry.

Further, simulation modelling of the environment is an important goal for AOSERP. Until the physical, chemical and biological processes and their interrelationships have been worked out for the region, prediction of man's probable impact on the environment remains out of reach.

One important line of enquiry with a strong affinity to purely hydrotechnical research relates to the assimilative capacity of the Athabasca River system for a variety of organic and inorganic compounds which may be introduced by man's activities in much higher concentrations than are in the system at present. This work will require close coordination amongst hydrogeologists, hydrologists, hydraulicians, chemists and biologists if the work is to adequately describe the natural system. A similar mix of skills will be required to fully assess the impacts of altered water quality on the ecology of the system.

Knowledge of the transport and deposition phenomena in Lake Athabasca and the Slave River will be required in the future to ensure that pollutants from the oil sands will not degrade waters in Saskatchewan via Lake Athabasca and the MacKenzie system via the Slave River. Preliminary work has also begun on these topics.

3.2 Groundwater

The major issues in groundwater research to be pursued by AOSERP include: 1) groundwater/surface water interaction; 2) the influence of in situ bitumen extraction on regional flow systems and the related issues of groundwater and surface water quality impingement by process and waste waters; 3) ground deformation phenomena related to in situ bitumen extraction and related seismicity; 4) reinstatement of local flow systems in reclaimed mine spoils and the related groundwater/surface water quality issues; 5) Groundwater supply management in the face of competing uses for the resource and the possibility of overuse. A major research program is being developed in concert with the Alberta Research Council in the Cold Lake region to address some of these questions. It is planned to use that experience in data base management and regional modelling to develop a parallel effort in the Athabasca oil sands region.

In addition, a passive seismic monitoring array is operational in the Cold Lake Oil Sands as part of a second research program which will study ground deformation problems related to in situ extraction of bitumen.

4.0 Conclusion

After seven years and about \$2.0 x 10^7, AOSERP has established a significant environmental and hydrotechnical information bank on the Athabasca Oil Sands region. A similar effort has been initiated in the Cold Lake Oil Sands. The initial period of AOSERP history has been taken up with baseline data gathering and storage. Data interpretation is underway in a number of areas, but much remains to be done.

Simulation modelling will preoccupy the program in its later stages and some of this work has been initiated.

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