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CIRCULATION OF WATER AND SEDIMENT IN THE ATHABASCA DELTA AREA

by

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ALBERTA OIL SANDS
ENVIRONMENTAL RESEARCH PROGRAM

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The Hon. J.W. (Jack) Cookson
Minister of the Environment
222 Legislative Building
Edmonton, Alberta

Sir:

Enclosed is the report "Circulation of Water and Sediment in the Athabasca Delta Area".

This report was prepared for the Alberta Oil Sands Environmental Research Program, through its Water System, under the Canada-Alberta Agreement of February 1975 (amended September 1977).

Respectfully,

W. Solodzuk, P. Eng.
Chairman, Steering Committee, AOSERP
Deputy Minister, Alberta Environment

This report is made available as a public service. The Department of Environment neither approves nor disagrees with the conclusions expressed herein, which are the responsibility of the authors.

ERRATA

Report 123 (Project WS 3.3.1)
Circulation of Water and Sediment in the
Athabasca Delta Area

page 59, 1st paragraph: suspended

page 77, 2nd paragraph: which

page 133, last paragraph: (by Csanady 1963)

The symbol μ has been left out of μm and μS on the following pages:

page 53, 3rd paragraph

page 55, 3rd paragraph

page 58, 2nd paragraph

page 81, 2nd paragraph

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ABSTRACT

The objective of the study was to describe how water and sediment from the Athabasca River are distributed through the delta system and how they circulate and mix in Lake Athabasca and flow through to the Slave River, with a view to understanding the pathways and destinations of contaminants that might reach the Athabasca River. Study components included literature reviews, remote sensing interpretations, field investigations and mathematical analyses. The project was viewed as a first stage study to sketch the essentials of the system and to outline needs and methodologies for a better definition.

General literature reviews cover briefly the hydrology of lakes, the mechanics of circulation and mixing in lakes and delta processes, with particular attention to circulation and mixing. The hydrology of principal lakes and channels in the study area is summarized using mainly information from past studies.

A series of selected satellite images and high-level aerial photographs taken between 1973 and 1978 is analyzed qualitatively to yield information on circulation and mixing. Limited previous water quality information is analyzed to supplement the remote sensing information.

Three field investigations were conducted in September 1979, March 1980 and June 1980. Data collected included water depths, current velocities, water quality parameters, and sediment concentrations. A special study of dispersive mixing was conducted during the June 1980 investigation. Efforts to obtain concurrent satellite data were unsuccessful, but field data have been compared against satellite data from an overpass about 9 days later.

Secondary studies reported included calculations of jet characteristics from delta distributary inflows, estimates of the zone of influence of lake outflows, and a consideration of the potential for mathematical and physical modelling of the system.

Conclusions are stated with regard to (i) the zones of Lake Athabasca occupied by Athabasca River water under various conditions, (ii) mixing of river water with lake water, (iii) interflows between Lake Athabasca and Mamawi Lake, (iv) sediment deposition and throughflow, (v) appropriate investigative techniques, (vi) mathematical and physical modelling, and (vii) implications regarding the transport and deposition of contaminants.

Brief recommendations are made regarding further studies.

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The study was initiated as a result of a joint proposal by Northwest Hydraulic Consultants and Alberta Research Council, which arose out of previous studies conducted separately by these organizations for the program. The project was administered as a contract between the Program and Northwest Hydraulic Consultants Ltd. as prime contractor, with Research Council as sub-contractors. The sub-contractor was responsible mainly for the circulation and mixing analyses, and the prime contractor for the hydrologic and sedimentation analyses; remote sensing interpretation and field studies were conducted jointly.

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1. INTRODUCTION

A general map covering most of the area of interest is shown in Figure 1.

1.1 OBJECTIVE AND SCOPE

The objectives of the study were specified in the contract as follows:

1. To estimate and describe how water from the Athabasca River is distributed through the delta system under various flow and ice conditions and at various levels of Lake Athabasca.
2. To estimate and describe the circulation and mixing of river water in Lake Athabasca under various conditions and their relationships to outflows to the Slave River and to cross-connections with Mamawi Lake and Lake Claire.
3. To describe the distribution, circulation, and deposition of sand and fine sediment carried to the mouth of the Athabasca River, both in the delta and in Lake Athabasca.
4. To relate flow specific processes to the possible contamination of the Athabasca River delta by upstream sources.

The study was divided into two phases. Phase I comprised mainly office studies and a one-day field reconnaissance in September 1979. It was completed in February 1980 by submission of an interim report, which was reviewed by a number of people. Comments by reviewers were taken into account in planning details of Phase II.

Phase II comprised mainly the planning, execution and interpretation of a field program in June 1980, plus further literature reviews and analytical studies.

Details of project tasks were specified in the contract as follows:

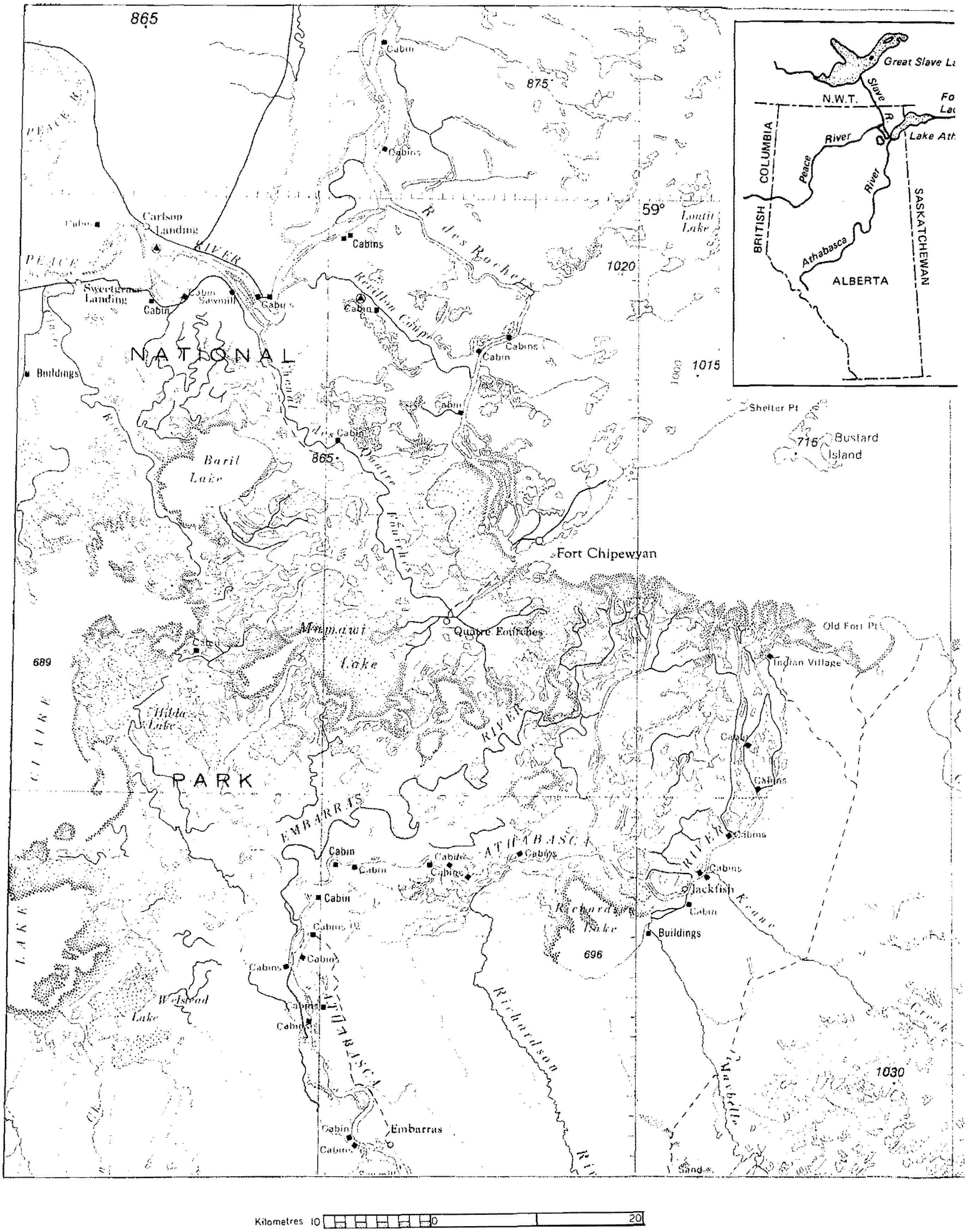

Figure 1. Map of study area. Based on 1:500 000 National Topographic Sheet 74 NW.

1. Review and synthesis of existing information: Summarize existing literature on the subject of the hydraulics and hydrology of the Athabasca Delta area, both in a natural state and as altered by control structures, and relate to general knowledge of flow in deltas as indicated by the scientific literature. Consolidate and analyze additional available data on flows through various components of the systems and the relationship of flow components to total inflows, lake conditions, and ice conditions.
2. Remote Sensing: Assemble and analyze available aerial photographs, satellite imagery, and related material to discern patterns of circulation and distribution of Athabasca River water under various conditions of flow, ice, etc.
3. Analytical Studies: Conduct a preliminary analysis of the potential for mathematical and/or physical modelling of the water and sediment flow systems.
4. Field Studies: After analyzing available information, plan and conduct a limited field program to obtain selective information on flow velocities, sediment concentrations, and water origin at various points in the delta and lake system. It is intended that the field program should be limited to a total period of about 2 weeks, and should be operated to coincide with special aerial observations where appropriate. If appropriate, arrange for special aerial photography or other form of remote sensing to obtain additional information in association with limited field measurements for 'ground truthing'.
5. Final Report: Prepare a report detailing the results of all studies, summarizing conclusions, and assessing the possibilities for predicting flow and sediment

> deposition in all likely combinations of controlling conditions. Recommendations for possible extension of the data collection and predictive aspects of the study would be included. Primary attention should be given to presenting an overview of the physical operation of the delta and lake system, and to assessing the implications for biological management and effluent control."

The present report does not necessarily reflect the weighting of various study items implied by the above specifications, because perceptions of priorities and possibilities have been somewhat altered in the course of the work. Certain topics not specifically mentioned in the original specifications have been found important, particularly the analysis of water quality data. It is considered appropriate to quote the following extract from the original study proposal: "It would be unrealistic to claim that a full picture of such a complex hydraulic system can be built up on the basis of a one-year project. Accordingly, the present project is viewed as a first stage study that will, so far as possible, utilize existing information to semi-quantitatively sketch the essentials of the system, that will collect only a limited amount of field data of a reconnaissance nature, and that will devote attention to outlining needs and methodologies for better definition of the system."

1.2 PAST AND PRESENT RELATED STUDIES

Scientific information relevant to the present study was first usefully assembled in the Peace-Athabasca Delta Symposium held in 1971 (University of Alberta 1971). This symposium, which resulted from multi-disciplinary concerns and preliminary studies about the effects of Peace River regulation by B.C. Hydro, contained four papers on the geology and hydrology of the area, as well as papers on biologic, socio-economic and legal aspects.

Further detailed studies of the area resulted from a federal-provincial project conducted in 1971-73, and were reported in a Technical Report with extensive Appendices (Peace-Athabasca Delta Project 1973). Appendices cover hydrological and ecological investigations and various support studies of a historical, socio-economic or legal nature.

Further hydrologic studies have been conducted by federal and provincial agencies under the auspices of the Mackenzie River Basin Study initiated in 1976 (Sydor et al. 1979). Studies have been mainly concerned with development and refinement of a mathematical flow simulation model for relating discharges and water levels throughout the lake and channel system. These studies are continuing.

Other relevant studies previously conducted under the Alberta Oil Sands Environmental Research Program include a surface water hydrology synthesis for the oil sands area (Neill and Evans 1979), a study of winter mixing conditions in the Athabasca River (Beltaos 1979) and a review of regional water quality in the oil sands study area (Seidner 1979).

While Phase II of the study was in progress, Alberta Environment commissioned a series of engineering and environmental studies for the proposed Slave River hydro-electric project at Mountain Rapids near the Alberta-NWT boundary. Certain configurations for this project, advantageous from an operational viewpoint, could significantly affect outflow conditions from Lake Athabasca and water levels in the lake. Specified environmental studies therefore include investigations of project impact on processes considered in this study. For this reason, field studies conducted in June 1980 were to some extent overlapped with consultants' studies for the Slave River project. Interim reports on 1980 environmental studies have been submitted to Alberta Environment by the various consultants involved.

A final draft report was submitted for review in February 1981. It was subsequently amended in minor particulars in order to meet the more specific criticisms made by reviewers. Regrettably it was not found practicable to satisfy all the criticisms and suggestions received.

2. LITERATURE REVIEWS

This part of the report contains brief reviews on the hydrology of lakes, on circulation and mixing processes in lakes, and on delta hydrology and processes. The main purpose is to give some general background against which the characteristics of the Athabasca Delta situation can be judged. In accord with the main topic of the present study, more attention is given to circulation and mixing than to the other aspects.

As a general comment, it can be said that the literature on lakes deals mainly with lakes where inflows and outflows do not play a dominant role in circulations, and that the literature on deltas deals more extensively with marine than with inland deltas. In the literature consulted no reference has been found to the hydraulics of a situation comparable with the Athabasca Delta area, where inflows and outflows are close together at one end of a shallow lake.

2.1 HYDROLOGY OF LAKES

For general information on the hydrology of lakes, the main references consulted were Hutchinson (1957), Zumberge and Ayers (1964), and IAHS (1973). Hutchinson's Treatise on Limnology includes chapters on lake origins, morphology, water properties, water balance, hydromechanics, optical properties and thermal properties. Zumberge and Ayers' chapter in the Handbook of Applied Hydrology discusses classification, morphology, water level fluctuations, thermal properties, ice and hydromechanics. The IAHS symposium on Hydrology of Lakes is organized into sections on physico-geography, water balance, hydrometeorology (mainly evaporation), hydraulics, sedimentation and water management.

Hydraulic and hydromechanic aspects of lake currents, circulation and mixing, which are of primary interest for purposes of the present study, are reviewed separately in Section 2.2. The following notes refer mainly to water balance and sedimentation.

According to Hutchinson, sources of water are direct precipitation, river inflows, groundwater seepage, and springs. Losses occur via effluent channels (usually single) and by evaporation. The influence of fluctuations in inflow and evaporation on lake levels are complex and depend on various morphological and hydraulic factors. Most large lakes exhibit irregular fluctuations over periods of years and decades as well as more systematic seasonal fluctuations: these longer-period fluctuations are associated generally with climatic fluctuations affecting precipitation and evaporation. Systematic trends and discontinuities may be associated with basin land-use changes or alterations to outlet hydraulics. Writing in 1957, Hutchinson left open the question of whether there is a general tendency for fluctuations in the levels of large lakes to be synchronized throughout the world: he considered that the evidence suggested world-wide low levels in the middle 19th century and in the first quarter of 20th century.

Hutchinson notes the significance of density differences between river inflow and lake water. When inflow is less dense, it flows over the surface but is rapidly mixed by wind-generated turbulence. When inflow is denser because of suspended sediment, dissolved solids, or temperature, it descends to the lake bottom, tending to the right in large Northern Hemipshere lakes because of the earth's rotation. He also notes the occurrence of density currents on sloping lake bottoms, due to diffusion of dissolved material from bottom sediments into the adjacent water.

Zumberge and Ayers also discuss lake-level fluctuations with particular reference to the Great Lakes, noting that attempts to relate fluctuations to sunspots or other cyclic phenomena have not been successful. They note the significance of crustal movements in relation to water-level trends, and the effects of man-made works.

In the IAHS Hydrology of Lakes Symposium, twelve papers under the heading of physico-geography are concerned largely with investigative techniques, including radioactive and hydrochemical tracers, analysis of flow rates and circulation from temperature data, current metering by buoyant kites and radar tracking of drogues. Analytical aspects considered include calculation of overall and local turnover times, determination of water exchanges between lake segments and layers, and under-ice currents deflected by the earth's rotation.

Seven papers under the sedimentation heading in the same volume deal with significance of lake sediments and associated energy relationships, with measurement of sedimentation using radioactive tracers from fallout, with hydraulic model studies of currents and sediment movement, and with the shoreline dynamics and sediment balances of storage reservoirs. The first paper, by P.G. Sly of Canada Centre for Inland Waters, is similar to a later more complete review of lake sedimentary processes by the same author (Sly, 1978). Some points from the later review are as follows:

- most lakes in temperate regions mix vertically twice a year;
- inflows with high solids content may produce density currents and underflows;
- for lakes with fetches in the order of 20 to 200 km (comparable with Lake Athabasca), and wind speeds in the range of 15 to 20 knots, the so-called 'wave base' ranges from about 5 to 30 m: this is the depth below which wave action on sediments is of little account;
- there are notable differences between lacustrine and marine beach forms;
- in the nearshore zone, the effects of waves and currents are difficult to separate;
- in a transitional zone, between nearshore and deep lake zones, fine sand forms less than 10% of sediments, which consist mainly of variably mixed silt and clay;

- 'baroclinic' circulations due to density differences and pressure gradients, with velocities of up to 0.5 m/s, are important in transporting fine sediments through large lakes; currents due to the earth's rotation ('geostrophic') are also significant;
- sediment plumes and 'gyres' may arise from dispersal of inflows, from currents around shoreline features, and from wind-driven current systems;
- deep lake zones are usually characterized by very slow circulation and a uniform cover of clayey mud;
- settling of very fine particles is not possible in most lakes with circulation and upwelling, except under ice cover.

2.2 CIRCULATION AND MIXING IN LAKES

The phenomena of lake circulation and mixing are extremely complex because of the many factors which influence lake motions. Currents in a lake may be caused by (i) wind, which transfers momentum to the water, (ii) through-flow, and (iii) convection currents induced by unstable density gradients. In general two scales of water motion are usually of interest. These are large scale circulation patterns characterized by the time-averaged velocity field in the lake, and smaller-scale turbulent motions responsible for the diffusion of mass, momentum and heat. The distinction between large-scale circulations and turbulent diffusion is not always apparent, and the complete interaction between all scales of motion is one of the unsolved problems for turbulent flows in general and lake motions in particular.

Three methods have been used either separately or in conjunction to study circulation and mixing in lakes. These are (i) analytical studies, which solve a set of equations describing the motion in a lake, (ii) physical models, where a scale model of the lake is used to observe lake motion, and (iii) field studies, which actually measure the parameters of interest in the field.

In what follows, a general discussion of the main features of lake circulation and mixing processes will be given. A more detailed evaluation of the analytical and physical models used for the solution of lake circulation and mixing problems will be given later in section 7.2.

General references for lake circulation and mixing processes are Hutchinson (1957), Pond and Pickard (1978) and Fischer et al (1979). It should be noted that Pond and Pickard (1978) deal with dynamic physical oceanography and that physical oceanography and lake hydrodynamics have many areas of common interest.

2.2.1 Circulation

Of the many factors which influence circulation in a lake, Bengtsson (1978) lists the most important as lake morphometry, shore configuration, bottom conditions, wind exposition, general climatic conditions, relative position of inlet and outlet, the rotation of the earth, and density stratification. A common approach to quantify one or two of these effects is to simplify the governing equations of motion so that the phenomenon under consideration is isolated. A classic example of this type of analysis concerns the importance of the Coriolis forces on wind-induced lake circulation. The simplified equations consider the balance between the Coriolis forces and the vertical turbulent stress terms (see for example White 1974):

$$f\bar{v} + A\frac{\partial^2\bar{u}}{\partial z^2} = 0 \qquad \text{(x momentum equation)}$$

$$-f\bar{u} + A\frac{\partial^2\bar{v}}{\partial z^2} = 0 \qquad \text{(y momentum equation)}$$

where f is the Coriolis parameter given by $f = 2\,\Omega\,\sin\,\phi$ where Ω is the angular speed of the earth's rotation and ϕ is the latitude; A is the vertical (constant) turbulent eddy viscosity; and u and v are the horizontal velocity components. These equations, along with appropriate boundary conditions including a specification of the wind stress, were first solved by Ekman (1905) to give the horizontal velocity distribution with depth. The surface velocity as predicted from this analysis is exactly 45^0 to the right of the wind. Below the surface the so-called Ekman spiral is set up, the velocity decresing exponentially with depth and continuously turning to the right. At a depth d given by

$$d = \pi \sqrt{\frac{2A}{f}}$$

the predicted current is 4% of the surface current and is in a direction exactly opposite the surface current. This depth is called the depth of frictional influence and is the depth to which wind effects are transferred downwards by wind-induced turbulence. From empirical observations Ekman found that this depth was related to the wind speed by the relation

$$d = \frac{4.3\ W}{\sqrt{\sin\phi}}$$

where d is the depth (m), W is the wind speed (m/s) and ϕ is the latitude. Comparison of these two equations implies that for increasing wind speeds the vertical eddy viscosity increases.

One factor which influences the above analysis is the presence of a lake bottom. For lake depths very much greater than the depth of frictional influence, this analysis is reasonable within the limitations of the other assumptions utilized to derive the above equations. However for lakes whose depth is less than the frictional depth, a reverse Ekman spiral will be set up at the bottom which counteracts the wind-induced surface spiral. For lakes with depths less than about d/10, the surface spiral is cancelled by the bottom spiral, resulting in currents which are in the same direction as the wind (Pond and Pickard 1978).

Another situation in which Coriolis forces are important concerns the deflection of river-induced currents, which tend to the right in the northern hemisphere. Hamblin and Carmack (1978) studied this effect for a fjord lake in British Columbia and found that these river currents flow along the right-hand shoreline, independent of the prevailing wind conditions. A similar phenomenon has been observed by Wright and Nydegger (1980) for an elongate deep lake in Switzerland, and Tesaker (1973) has reported thinner ice along the right bank of Lake Sperillen in Norway.

The density of water exhibits a maximum at 4^{0} C. This phenomenon allows for the possibility of density gradients in a lake, as a result of the heat exchange between the lake and its surroundings. Depending on the stability of these density gradients the circulation may be suppressed or enhanced.

Generally in a lake under open water conditions there are three more or less distinct layers characterized by their vertical temperature (density) distributions (see for example, Hutchinson 1957). The upper layer, called the epilimnion, consists of relatively freely circulating warm water, and displays a very small and variable vertical temperature gradient. The middle layer, through which the temperature drops fairly rapidly with increasing depth, is called the metalimnion. The plane of maximum temperature gradient within the metalimnion is called the thermocline. In the third and deepest layer, called the hypolimnion, the very gentle fall in temperature with increasing depth is nearly exponential. The thermal behavior of lakes and the formation of a thermocline is at least qualitatively well known. In order to explain these processes the annual thermal cycle of a moderately deep temperate lake will be discussed (see, for example Ragotzkie, 1978). Starting in the spring shortly after the disappearance of the ice cover, the water in the lake attains a uniform temperature of 4^{0} C. Warming occurs at the surface, primarily by solar radiation and this warmed surface water is mixed downward by wind action. The warmed water is only a few degrees above 4^{0} C and is only weakly stable, therefore mixing can occur over a great depth. In all but the deepest lakes, the water will therefore remain at a uniform temperature to a few degrees above 4^{0} C. Continued surface warming results in the surface water becoming sufficiently buoyant to resist complete vertical mixing. The action of the wind, however, results in a thin surface layer of warm isothermal water. A large temperature gradient is set up just below this layer and correspondingly the stability is increased. This stable layer contains the thermocline. The thermocline separates the warmer epilimnion from the cooler hypolimnion. Periods of strong winds result in deeper mixing and the thermocline descends accordingly. This process continues through the summer and early fall as the lake is stably stratified, with most of the incoming heat being trapped in the epilimnion.

Sometime in the late summer or early fall there is a reversal of the direction of the net heat transfer at the water surface and the lake begins to cool. Since cooling occurs at the surface, the cooler and denser surface water descends convectively and cooling occurs throughout the epilimnion. The epilimnion temperature decreases nearly to that of the hypolimnion and further surface cooling aided by strong winds eventually results in a uniform lake temperature of 4^{o} C. Further cooling in the lake takes place isothermally except for the very deepest parts.

Ice formation can commence as soon as the surface water temperature reaches 0^{o} C. Usually ice first forms in shallow and protected bays. Generally ice formation occurs during calm conditions, often at night. During the ice-covered period the lake water is insulated from the wind and currents in the lake are mainly due to throughflow. Heating of the water can occur from the bottom sediments and also by absorption of radiation penetrating the ice cover. Snow cover inhibits this latter process considerably.

With the onset of spring, the snow cover softens and begins to melt and subsequently so does the ice. When the physical integrity of the ice sheet is essentially destroyed, a strong wind is able to break up the ice. Surface warming of the cold water is accompanied by strong vertical mixing due to the maximum density of water being at 4^{o} C. This vertical mixing results in a uniform lake temperature of 4° C and the cycle as described above repeats itself.

Two of the most important ways in which the stratification affects the circulation patterns in a lake are the behavior of a river inflow or an industrial discharge flowing into a lake and the effect of the thermocline on the vertical mixing processes in a lake. Both of these aspects have been reviewed by Sundaram et al (1969), for example. If the temperature of the inflow is greater than that of any part of the lake and hence of smaller density (assuming temperatures greater than 4° C), it will remain at the surface and will mix predominantly in the horizontal direction, vertical mixing being reduced because of the stable density gradient. If the temperature is lower than that of the lake surface then the river or discharge will sink, seeking the depth in the lake with same temperature. This effect has been observed in Kamloops Lake in British Columbia by Hamblin and Carmack (1978).

The thermocline, by definition the plane of maximum temperature/density gradient, acts almost as an impermeable barrier to vertical exchange between the epilimnion and the hypolimnion. The parameter which characterizes the vertical stability in a lake is the gradient Richardson number Ri, defined as follows (Fischer et al. 1979):

$$Ri = \frac{-g\partial\rho/\partial z}{\rho(\partial u/\partial z)^2}$$

where ρ is the fluid density, $\partial u/\partial z$ is the vertical velocity gradient, g is the gravitational acceleration, and z is positive upwards. Mixing is essentially inhibited when the Richardson number exceeds a critical value, in the order of 0.8 (Ellison and Turner 1959). The very large density gradient at the thermocline is generally sufficient to cause the Richardson number to exceed the critical value and to inhibit mixing between the hypolimnetic and epilimnetic water. For other stably stratified cases, the value of the Richardson number gives an indication of the relative importance of the buoyancy forces in reducing turbulent mixing.

Another important type of lake circulation phenomenon is the back and forth oscillation of lake level known as a seiche, much like the sloshing of water in a bathtub. There are two kinds of seiches: surface seiches and internal seiches. A surface seiche involves oscillation of the whole body of water, or of the surface layer in a stratified lake, while an internal seiche in a stratified lake represents the motion of the lower layer, the thermocline playing the role of the free surface.

Seiches may be free or forced. Free seiches can be considered special cases of standing waves, and it is possible to determine the period as a function of lake dimensions (see Wilson 1972 for example). A free seiche can occur when the water surface has been sloped in one direction, for example by a strong steady wind, and is released by a drop in the wind. Oscillations result from the restoring force of gravity tending to return the water surface to its equilibrium position. A forced seiche occurs when a transitory or periodic external force acts on the surface of the lake, the period depending on the characteristics of the external disturbance. The most common cause of a forced seiche is a pulse change in the barometric pressure, as in the passage of a squall. Resonance can occur when the period of the disturbing force matches the natural period of the free seiche, giving rise to large-amplitude oscillations.

Internal seiches can occur in stratified lakes and are set into motion when the thermocline becomes inclined, due to wind set-up for example. A sudden drop in the wind will then generate an internal seiche as well as a surface seiche. Internal seiches are of great importance from an ecological point of view because they tend to mix the hypolimnetic and epilimnetic waters, which normally are clearly separated.

The wind is the primary flow-generating mechanism in most lakes. Currents generated near the inlet and outlet by throughflow are usually of local significance only and have little influence on lakewide circulation patterns, except in the special case of long narrow lakes with important throughflow. However, where the inlet and outlet are relatively close together, circulation in the adjacent portion of the lake may be significantly affected by the inflow and outflow currents. Throughflow may also be important in the case of an ice-covered lake, where the ice cover insulates the lake water from the wind.

2.2.2 Mixing

Turbulence is by far the most important source of mixing in lakes. Lake turbulence is generated by direct wind action or by shear action of the currents. Turbulent diffusion is usually described analytically by the Fickian approach, that is :

$$F_x = -K_x \frac{\partial c}{\partial x}$$

where F_x is the diffusive mass transport in any direction x, K_x is the corresponding turbulent diffusivity, and c is the concentration of the mixing substance. Values for diffusivity have been determined by measurements in many different lakes, but the scatter is very large and no single value or relationship can be used with confidence.

Observations of mixing in lakes and other water bodies usually involve injecting a quantity of tagged particles (fluorescent dye for example) into the water and then following the travel and spread of the particles with time. Two injection techniques are commonly used: injection at a steady rate and instantaneous injection of a known volume (slug injection). It is instructive to consider the fate of a quantity of dye injected as a slug into a lake. To measure the spread of the dye cloud, a frame of reference is taken which travels with the cloud. By observing the concentration distributions at various times after injection an 'effective diffusivity' can be calculated from the expression:

$$K_x = \frac{1}{2} \frac{d(S_x)^2}{dt}$$

where S_x is the standard deviation of the concentration distribution in the x direction. The term 'effective diffusivity' is used here; equally valid would be 'dispersion coefficient', because unless the velocity field into which the dye is injected is spatially uniform, the presence of velocity gradients will enhance the mixing process. The combined mixing effect of diffusion and velocity gradients is termed dispersion; as pointed out by Ottesen-Hansen (1978), when a 'diffusivity' is calculated from a dye test it usually represents a dispersion coefficient. This is one of the factors responsible for the large scatter in reported lake diffusivities.

In addition to diffusion and differential advection, secondary vortices known as Langmuir circulations or windrows significantly affect vertical mixing . The axes of these vortex motions are aligned with the wind and they are manifested on the surface by the presence of foam or debris lines which represent the convergence zones of two adjacent cells. These vortex motions greatly enhance the vertical mixing in lakes and oceans and are known to inhibit horizontal diffusion because of the presence of the convergence zones (Csanady 1963). No satisfactory explanation for the occurrence of Langmuir circulations has been given so far, although many hypotheses have been offerred (Ottsen-Hansen 1978). Discussions of Langmuir circulations are given by Scott et al (1969) and Leibovich (1977).

The wind stress and the vertical density gradient are importance in vertical mixing. As was discussed previously, a stable vertical density gradient inhibits vertical mixing, the Richardson number being the parameter which indicates the magnitude of this effect. For stratified cases, Kullenberg et al (1973) have proposed the following dimensionally homogeneous formula for the vertical diffusivity:

$$K_z = \frac{8 \times 10^{-8} W^2}{Ri^2 \, du/dz}$$

where W is the wind speed, du/dz is the vertical velocity gradient, and Ri is the gradient Richardson number as before. Increasing wind speeds cause increasing turbulence levels, increasing the vertical diffusivity. However an increasing Richardson number, indicating increasing vertical stability, decreases the vertical diffusivity. For a neutrally stable water body, the density gradient is uniform with depth and the Richardson number is zero. Bengtsson (1973) proposed the following formula for the neutrally stable case:

$$K_z = 2.5 \times 10^{-5} hW$$

where h is the depth and W the wind speed.

Because of the complexity of the mixing processes and the fact that the velocity field must be known a priori, no comprehensive theory is available at the moment for predicting diffusion and mixing in lakes. Although many theoretical models are available which solve the governing equations with the aid of various simplifying assumptions the spatial and temporal variation of diffusivity, which is an essential parameter in the equations, cannot be predicted with any confidence. Therefore for practical purposes field studies are required to evaluate these coefficients. Field studies necessary to define the diffusivity coefficients in space also provide direct information on mixing, which may eliminate the need for extensive mathematical treatment in many practical cases.

2.3 DELTA HYDROLOGY AND PROCESSES

The main references consulted for general information on delta hydrology and processes were Wright (1978), Axelsson (1967) and IAHS (1970).

The chapter on river deltas by Wright (1978) discusses their occurrence and distribution, general characteristics, formative processes, sediments and sedimentary structures, and geometric variability. Key points include the following:

- deltas typically contain subaerial and subaqueous parts, both divided into abandoned and active areas;
- as the delta advances, distributary channels extend by formation of subaqueous levees;
- delta shorelines are ephemeral: highly irregular shorelines (as in the Athabasca Delta) are characteristic of low wave energy environments;
- salient processes determining delta pattern include river-mouth diffusion, tides, waves, currents and subsidence.

With regard to diffusion and dispersion at river mouths, Wright refers to a number of detailed studies and concludes that spread patterns depend primarily on inertia of river inflows, on bed friction, and on density differences between inflow and ambient water. In the case of high inflow velocities, large ambient depths, and low density contrasts, inertia dominates and the inflow diffuses as a three-dimensional turbulent jet. With low ambient depths (as in the case of Lake Athabasca), diffusion is mainly horizontal and bottom friction assists deceleration and expansion. The effect of density differences has been studied mainly for the (marine) case of inflows that are lighter than the ambient fluid, not denser as tends to be the case with high sediment loads entering a lake.

Axelsson's detailed study of the Laitaure Delta in northern Sweden includes a review of deltaic morphology and processes, and in particular a discussion of the complex flow patterns at a delta front. Key points include the following:

- flow from distributaries resembles expansion of submerged jets;
- three types of inflow situation are recognized: (i) the inflow is denser than the ambient fluid and forms a turbidity current which inhibits mixing; (ii) the inflow is of similar density and (given sufficient depth offshore)

mixes readily in three dimensions, producing the classical delta type with top-, fore- and bottom-set beds; and (iii) the inflow is less dense and spreads over the surface as a buoyant plane jet (marine case);

- for foreset beds (steeply inclined) to form at the delta front, the distributaries must carry bed load right up to their mouths;
- fine-grained deltas are characterized by gently inclined frontal profiles (like the Athabasca Delta);
- density currents may form with relative density differences as low as 0.0003 between the inflow and receiving water; this can be caused by a suspended sediment or dissolved salts difference of about 500 mg/L, or a temperature difference of one to two degrees;
- large deltas often advance areally in an irregular manner, with alternation of constructional and destructional phases, particularly in the presence of waves and coastal currents.

The IAHS (1970) publication in two volumes records a symposium on hydrology of deltas held in Bucharest in 1969. A large proportion of the material is concerned with the Danube delta. The first volume contains mainly papers of a geomorphologic nature, but one or two papers deal with distribution of flow among delta distributaries and with relationships between flows and channel characteristics. The second volume is more concerned with hydrology hydraulics and hydrogeology: topics of interest include channel network analysis, jet dispersion at channel mouths, ice regimes, tracer studies of sediment movement, and physical modelling of delta flows by aerodynamic analogue. In summary, the publication does not include much synthesized material on delta processes and hydrology.

From the foregoing it can be seen that the irregular shoreline and very flat frontal slopes of the Athabasca Delta are characteristic of a fine-grained delta in shallow water without much action by waves and coastal currents. It can be expected that the distributary inflows will spread more or less as plane jets with substantial retarding effects from bottom friction.

It seems likely that depths in the affected part of Lake Athabasca are everywhere too shallow for development of density currents. While there may be a tendency for the Embarras River and Fletcher Channel inflows to curve west at times under the influence of lake outflows, Goose Island Channel and Big Point Channel inflows might be expected to curve east under the influence of the earth's rotation, especially under ice conditions when wind-induced lake currents are absent.

3. HYDROLOGY OF PRINCIPAL LAKES AND CHANNELS IN THE STUDY AREA

The principal drainage basins feeding the study area are shown in Figure 2. Details of drainage in the study area are shown in Figure 3.

3.1 NATURAL FLOW SYSTEM PRIOR TO PEACE RIVER REGULATION

Lake Athabasca straddles the Alberta-Saskatchewan border just south of the territorial boundary. The shallow southwestern end of the lake is bounded to the south and west by a large deltaic area of about 3800 km^2 that includes the Athabasca Delta, Lakes Claire, Mamawi and Baril, and the Peace Delta.

The surface area of Lake Athabasca is about 7850 km^2. Its volume is not accurately determined but is in the order of 200 km^3, based on limited information.[1] The average annual outflow is about 45 km^3, of which the Athabasca River contributes about 52% and the Fond du Lac River (at the east end) about 21%, the remaining 27% being made up from a number of smaller tributaries around the lake and direct precipitation on the lake itself (Figure 4). Outflow from Lakes Claire and Mamawi, which originates mainly from the Birch River system discharging into Lake Claire, accounts for less than 3% of the average annual outflow and essentially bypasses Lake Athabasca. The annual range in lake levels, prior to Peace River regulation, was normally about 2 m, corresponding to a volume change of about 15 km^3.

Lake Athabasca drains into the Peace River via Riviere des Rochers and Chenal des Quatre Fourches, which join the Peace River to form the Slave River (Figure 3). The rate of outflow from Lake Athabasca depends on water levels in Lake Athabasca and in the Peace River. Prior to closure of B.C. Hydro's Bennett Dam on the Peace River in December 1967, water levels in the Peace River at the confluence with the Lake Athabasca outflow were often high enough in early summer to restrict or reverse the outflow from Lake Athabasca,

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[1] Depths shown on Canadian Hydrographic Service Chart no. 6310, 1973 edition.

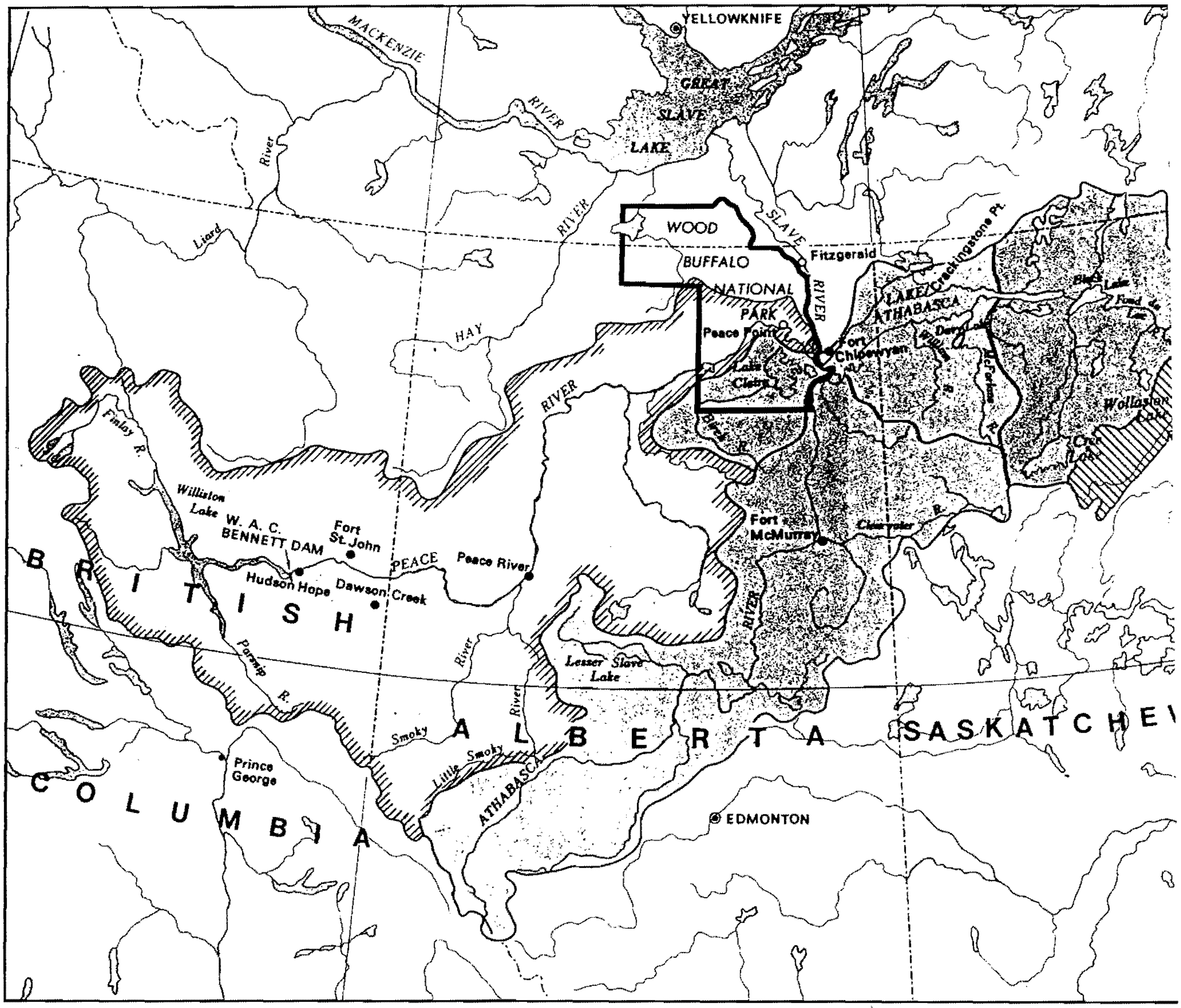


Figure 2. Drainage basins of the Peace and Athabasca rivers and other inflows to Lake Athabasca. (Peace-Athabasca Delta Project 1973).

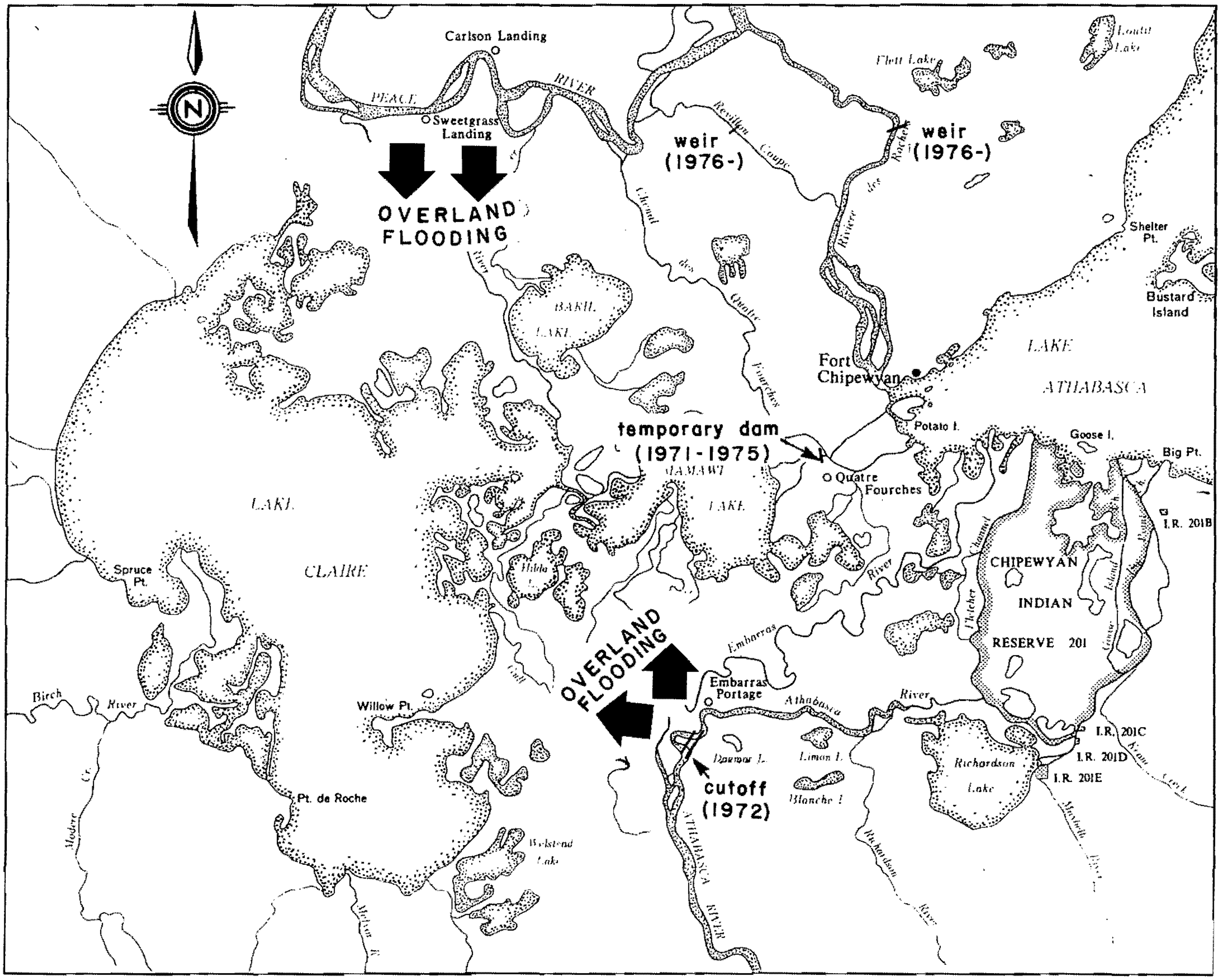
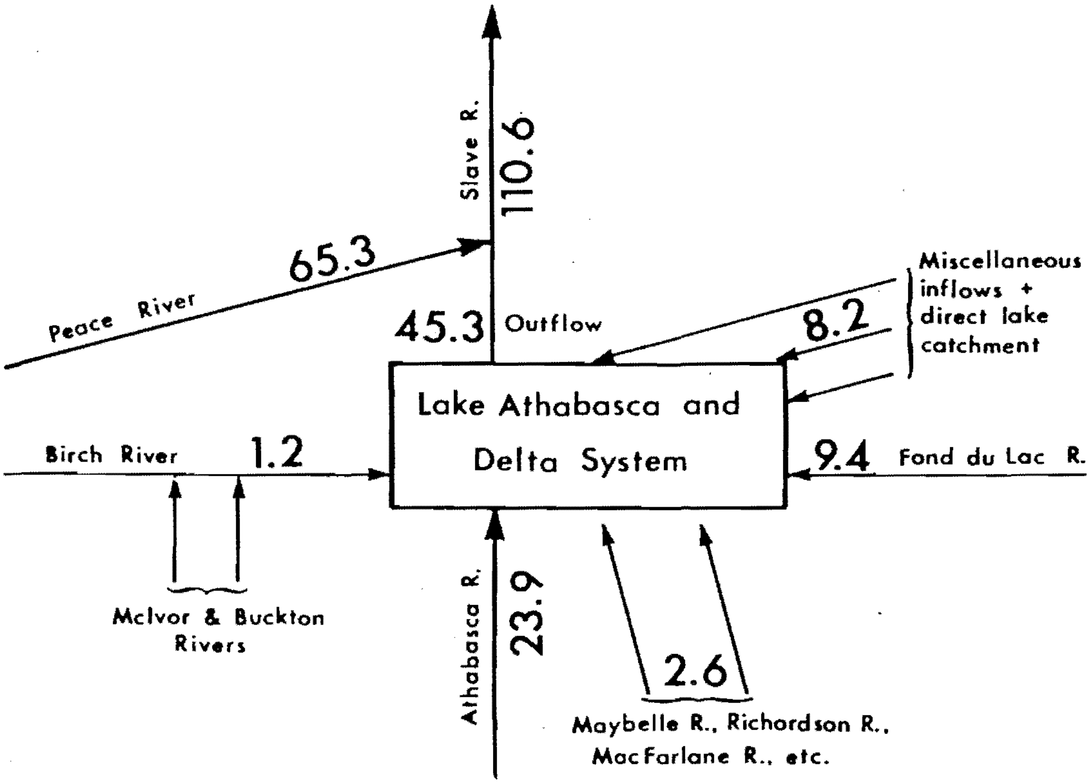


Figure 3. Details of drainage in the study area. (Peace-Athabasca Delta Project 1973).



Units of km^3/yr

Figure 4. Mean annual water balance (based on Neill and Evans 1979).

thus maintaining or raising the water levels of the lake. When the lake level is high, a large area of low-lying land is flooded.

Lakes Claire and Mamawi, through which flow from the Birch River system passes to reach the Lake Athabasca outflow system, have surface areas of about 1160 km^2 and 160 km^2 respectively, and volumes of about 1.2 km^3 and 0.16 km^3 respectively. The average annual inflow from the Birch River is about 1.2 km^3. Outflow from Mamawi Lake mostly passes to the Peace River via the northwest fork of Chenal des Quatre Fourches, but part sometimes passes along the northeast arm to the western corner of Lake Athabasca and thence into Riviere des Rochers. Flow out of Lake Athabasca via Chenal des Quatre Fourches, which accounts for about 10% of the total outflow from the lake, sometimes backs up into Lake Mamawi via the southwest arm.

3.2 EFFECTS OF BENNETT DAM AND SUBSEQUENT MITIGATIVE MEASURES

Bennett Dam, situated on the Peace River in British Columbia 1170 km upstream of the Peace-Athabasca confluence (Figure 2), controls about 50% of the flow in the Peace River at the confluence. The dam was closed in December 1967, and filling of the reservoir (Williston Lake) was completed by 1972. The filling process entailed witholding a volume of approximately 60 km^3 from the Peace River in Alberta.

The predicted effect of the hydro project on Peace River monthly flows near the Peace-Riviere des Rochers confluence is shown in Figure 5. The recorded effect on June monthly flows up to 1978 is shown in Figure 6. Since the dam became operational, the average monthly flow for June has been reduced from about 7500 m^3/s to about 4200 m^3/s. The corresponding reduction in water levels at the Peace-Rochers confluence is about 3 m.

Information presented at the Peace-Athabasca Delta Symposium (University of Alberta, 1971) indicated that reservoir filling had reduced annual maximum levels in Lake Athabasca by as much as 1.2 m and that after completion of filling the effect of

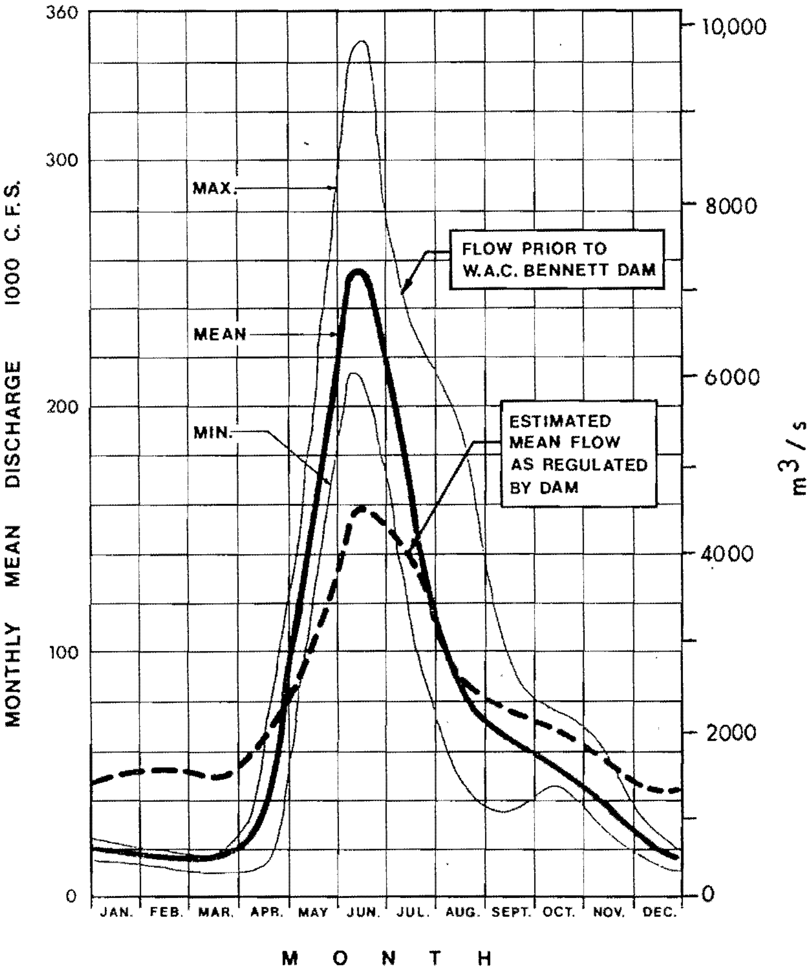


Figure 5. Predicted effect of Peace River regulation at Bennett Dam on monthly flows at Peace Point (Peace-Athabasca Delta Project 1973).

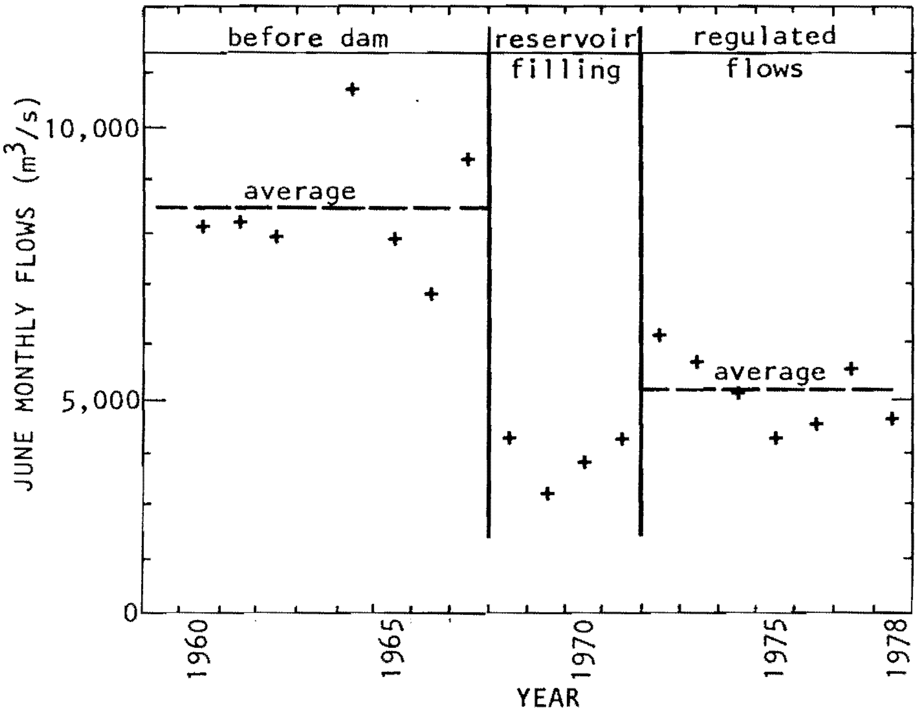


Figure 6. Actual effect of Peace River regulation on June monthly flows at Peace Point.

regulation would be to reduce annual maximum levels by about 0.7 m, possibly by more in the long term if degradation occurred in the outflow channels. Following the Symposium, intergovernmental studies were initiated and measures were taken to mitigate the hydraulic effects of Peace River regulation, which were judged detrimental to wildlife habitat in the delta area (Peace-Athabasca Delta Project, 1973). A temporary dam was first built in the fall of 1971 across the southwestern arm of Chenal des Quatre Fourches controlling the outlet of Lake Mamawi, to hold back flow from the Birch River and maintain levels in Lakes Claire and Mamawi (Figure 3). In 1972 water levels were generally restored to pre-1968 conditions, as a result of high flows, a spring ice-jam on the Peace River, and completion of reservoir filling. The temporary dam was washed out by spring floods and re-built on several occasions, but was finally abandoned in December 1975. Since that time, water levels in Lakes Claire and Mamawi have been approximately the same as those of Lake Athabasca, the slopes of the connecting channels being very flat.

Between June 1975 and March 1976, permanent control structures, designed to maintain Lake Athabasca and the other lakes at levels close to those existing prior to Bennett Dam, were constructed on the Riviere des Rochers and Revillon Coupe channels (Figure 3). The structures consist of fixed-crest, rockfill weirs designed to control the outflow from Lake Athabasca when Peace River levels are low.

In August 1972 a pilot cutoff was constructed across a meander bend of the Athabasca River near Embarras Portage (Figure 3). The object of the cutoff was to stop the Athabasca River from cutting into the Embarras River, its farthest upstream distributary. It was feared that if this were allowed to occur, the Athabasca River would form a principal channel to Lake Claire, thereby short-circuiting the Athabasca Delta. By 1976 the cutoff had developed to the point that it had captured the majority of the Athabasca River flow, thus successfully halting the migration of the meander loop towards the Embarras River (Northwest Hydraulic Consultants Ltd. 1978).

Further changes in the hydrology of the system will occur in future as a result of projected hydro developments on the Slave River, additional developments on the Peace River, and possible developments on the Athabasca River.

3.3 PRESENT REGIME OF FLOWS AND WATER LEVELS

Mean monthly discharges for the Athabasca, Birch and Fond du Lac rivers are listed in Table 1. Whereas the inflow from the Fond du Lac River varies little throughout the year, the Birch and Athabasca rivers exhibit relatively large differences between winter and summer flows. High summer inflow volumes from the Athabasca River, coupled with restricted lake outflows due to Peace River water levels, historically caused a sharp rise in lake levels in late June and early July.

Statistics on annual flow volumes and annual maximum flows for the Athabasca River over the 20-year period 1958-77 are given in Table 2. Year to year variations in flow volumes are modest, but variations in annual peaks are quite severe. Corresponding maximum annual flow statistics are also shown for the Peace River: although there is a noticeable effect of regulation by Bennett Dam, it is notable that the peak of 1974, after completion of reservoir filling, was virtually the same as the previous highest value of 1964. One of the satellite pictures later discussed herein reflects conditions following the 1974 Peace River flood, when reverse flow to Lake Athabasca and the other delta lakes occurred.

The Athabasca River enters Lake Athabasca through a system of distributaries, of which the principal channels from west to east are Embarras River, Fletcher Channel, Goose Island Channel and Big Point Channel (Figure 3). There are no continuous gauging stations on these channels, but irregular discharge measurements have been made since 1971 by Alberta Environment and by Water Survey of Canada. These have been analyzed to determine percentages of

Table 1. Mean monthly flows of Athabasca, Birch and Fond du Lac rivers.

Month	Mean discharge for the month Athabasca R. m^3/s	 Birch R. m^3/s	 Fond du Lac R. m^3/s
January	118	1.4	241
February	169	1.0	214
March	169	0.7	201
April	553	43	205
May	1172	108	317
June	1384	58	400
July	1451	71	388
August	998	41	366
September	835	46	338
October	618	41	339
November	345	16	317
December	217	3.9	275
Mean for year	675	36	300

Table 2. Flow statistics for Athabasca and Peace rivers, 1958-77.

Statistic	Athabasca River at Fort McMurray[a] Annual flow volume in km^3	Athabasca River at Fort McMurray[a] Annual max. flow in m^3/s	Peace River at Peace Point[b] Annual max flow in m^3/s
Mean value 1958-77	21.5	2560	8270
Standard deviation	3.4	1000	2300
Lowest in period	15.3	850	3910 (1970)
Highest in period	27.9	4700	11930 (1964,1974)
Range	12.6	3850	8020
Range as % of mean	59%	150%	97%
Mean value 1959-67	(prior to Bennett Dam)		9720
Mean value 1967-71	(during reservoir filling)		6250
Mean value 1972-77	(since reservoir filled)		7680

[a] Add approximately 10% for inflow volumes to Lake Athabasca. Relationship of peaks at delta to peaks at McMurray is not well defined.

[b] Essentially the same as at Peace-Athabasca confluence.

Athabasca River flow in the four distributaries. Table 3 shows, for example, flow distributions indicated by the data for 1977. On the basis of all the available data, it appears that the average distribution is more or less as indicated in Figure 7, but there are considerable variations from time to time. No systematic change in proportions could be discerned according to season or to magnitude of total flow.

It is notable that the distributary flows increase progressively from west to east. This reflects the progressive build-up of delta sediments from west to east that has caused gradual migration of the main river outflow to the east.

It has been stated (Peace-Athabasca Delta Project 1973) that the distributary channels are presently over-extended to the east and that in the natural course of events a major shift of the active lobe to the west could be expected, with discharge into Lake Claire or Mamawi Lake. As previously noted, a cutoff was constructed near Embarras Portage in 1972 to prevent such a development.

The major outflow channels from Lake Athabasca are Riviere des Rochers and Chenal des Quatre Fourches. The Revillon Coupe is a sub-distributary of the Riviere des Rochers (Figure 3). Some outflow occasionally occurs via Baril Lake and Baril River (Peace-Athabasca Delta Project 1973), but it is probably insignificant compared to flow in the other outflow channels. The average outflow distribution, based on limited discharge measurements taken since completion of the present control structures in March 1976, appears to be approximately as follows:

Riviere des Rochers:	90% of lake outflow
Chenal des Quatre Fourches:	10% of lake outflow

The outflow channel data show that occasionally there is a flow reversal in the Chenal des Quatre Fourches, when water enters Mamawi Lake from the Peace River. Thus occasional flooding of the Delta by the Peace River can still be expected, though not as frequently as occurred prior to completion of Bennett Dam. Water level data for the outflow channels at their confluences with the Peace River

Table 3. Flow distribution in principal Athabasca River distributaries, 1977

Date	Percent of Athabasca River flow[a] in distributary			
	Embarras River	Fletcher Channel	Goose Island Channel	Big Point Channel
17 January		14.0		
20 January			43.7	49.8
3 February			43.9	54.5
8 February		12.2		
23 February			38.2	47.9
28 February		13.1		
9 March		12.1		
10 March			43.3	47.4
23 March			38.0	45.1
25 March		12.0		
6 April			27.5	34.6
7 April		8.7		
20 May	14.4	17.1	27.5	34.3
31 May	14.1			
1 June		17.9		
3 June			22.0	28.7
13 June	15.4	19.4	34.1	41.6
28 June	12.7	18.9	31.3	37.2
12 July	13.4	16.2	28.9	33.8
25 July		19.1	31.6	37.5
26 July	14.1			
9 August	12.7	19.6	33.3	38.2
24 August	9.4	19.6	32.4	45.9
7 September	11.8			
12 September		19.0	32.2	38.4
19 September	7.6	15.6	34.3	45.4
4 October	10.3	16.9	31.0	33.9
Mean	12.4	16.0	33.7	40.8
Standard Deviation	2.4	3.4	6.1	7.0
Adjusted Mean[b]	12	15	33	40

[a] Athabasca River flow as reported at Embarras after 22 March, and as adjusted from Fort McMurray data for earlier dates.

[b] Adjusted to total 100%.

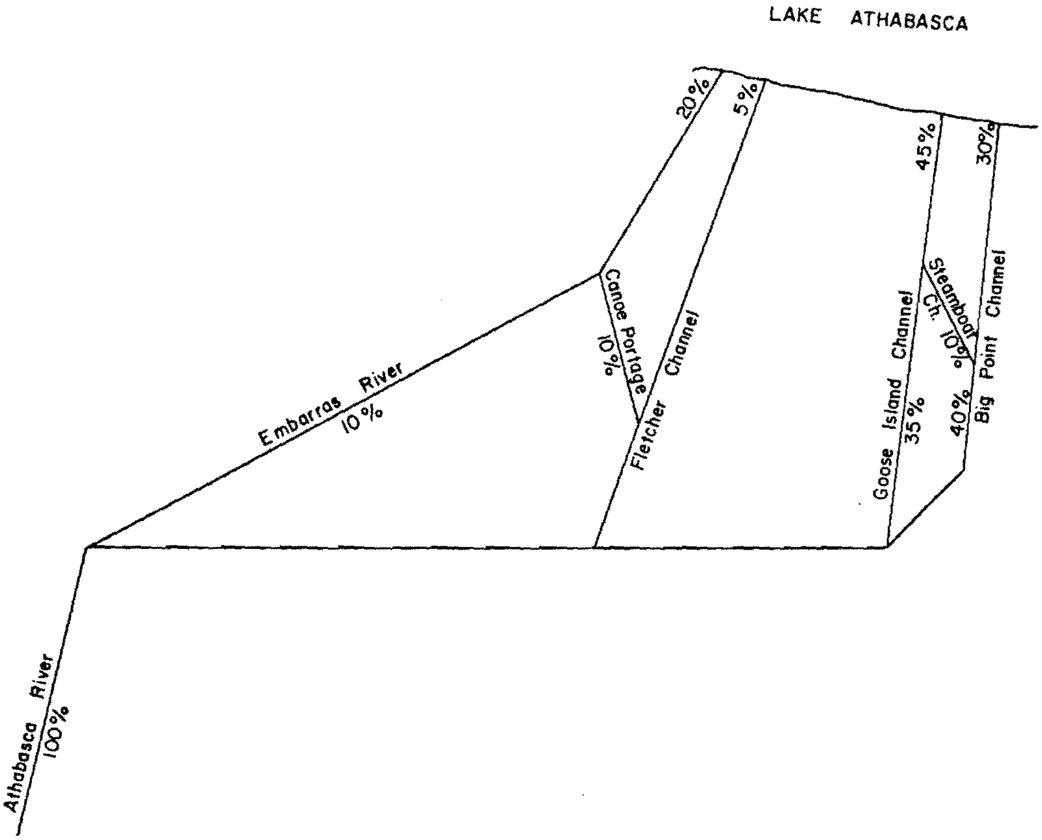


Figure 7. Approximate average distribution of Athabasca River flow between four main delta distributaries.

occasionally indicate water surface elevations higher than those of Lake Athabasca; however, there is some uncertainty over gauge datums. Water Survey of Canada publications note that water levels "are referred to approximate Geodetic Survey of Canada datum".

Available discharge data for Riviere des Rochers since completion of the control weirs in March 1976 are plotted versus Lake Athabasca water levels in Figure 8. A tentative open water rating curve for weir control has been drawn. Open water points that fall well above the indicated curve are probably affected by backwater from the Peace River. Data points for ice conditions plot up to 1.2 m above the indicated open water curve, and are quite erratic.

It was predicted that morphologic changes would occur in the outlet channels following completion of the Bennett Dam, due to the altered pattern of flows resulting from lower water levels in the Peace River and Lake Athabasca (Kellerhals 1971). These predictions did not take into account the remedial measures later undertaken to restore Lake Athabasca levels. Any morphologic changes would be manifested by a shift in the rating curve of the outflow channels. The data for 1976 to 1978 shown in Figure 8 do not indicate any shift, but it is perhaps premature to conclude that none will occur in future.

Lake Athabasca water level records since completion of the control weirs in March 1976 indicate a smaller range of levels than occurred under natural conditions prior to 1967. Maximum and minimum levels are summarized in Table 4 for both the natural system and the present system with control weirs. Although only three years of data are available for the present system, the values shown are thought to be reasonable approximations of future lake levels. It appears from Table 4 that under the present system the mean maximum lake level is approximately the same as under historical conditions, while the mean minimum level is nearly 1 m higher than the historical value.

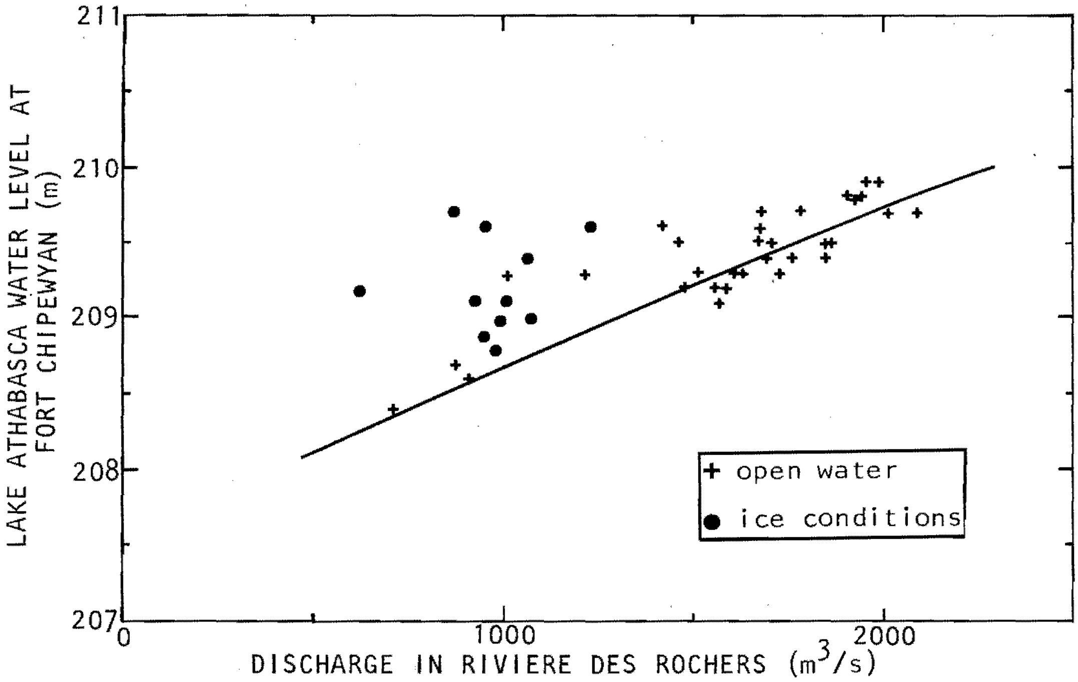


Figure 8. Lake Athabasca water level versus discharge in Riviere des Rochers. Based on data for 1976-78.

Table 4. Lake Athabasca water levels.

Period	Mean annual max.		Mean annual min.		Difference
	No. of data	Lake elev. m	No. of data	Lake elev. m	m
1935-70[a]	36	209.9	23	207.9	2.0
1976-80	5	209.8	2	208.4	1.4

[a] From Kellerhals 1971.

Mathematical routing models have been developed for relative inflows, outflows and water levels in the Delta area. The first such computer models were used in the Peace-Athabasca Delta Study for the design of the control structures. A model is presently being developed that will allow evaluation of the performance of the structures and that can be integrated with a comprehensive Mackenzie River Basin Model whose development was initiated in 1976 (Sydor et al. 1979).

3.4 SEDIMENT TRANSPORT AND SEDIMENTATION

The Athabasca River constitutes the main source of sediment input to Lake Athabasca under present conditions. Part of the inflowing sediment is deposited in the growing Athabasca Delta, and part passes through to the Slave River, mainly via the Riviere des Rochers. An attempt will be made to indicate the quantities of sediment inflow and outflow and their distributions in space and time, but the sparsity of the data base permits only a rough picture to be drawn. Sediment data for the Athabasca River were obtained from Water Survey of Canada publications, and data for the delta channels and Lake Athabasca outflows channel from Alberta Environment files.

Table 5 summarizes data on annual suspended sediment loads in the Athabasca River from 1969 to 1977. The annual totals given are for the 5-month season 1 May through 30 September only, but limited full-year data indicate that on a long-term average basis, this season probably accounts for over 90% of annual totals. The data for different years are from three different hydrometric stations, but differences in annual totals due to station location are believed to be unimportant. In summary, the table indicates a mean annual sediment inflow to Lake Athabasca of approximately 8 million tonnes. The standard deviation of 3.2 million tonnes reflects a high year to year variability. Roughly half of the annual inflow usually occurs in one month, usually June, July or August. Roughly 10% of the annual inflow often occurs in one day.

Table 5. Suspended sediment loads in Athabasca River, 1969-77.

Year	1 May-30 Sept sediment total load 10^6 tonnes	Highest monthly sediment load month	10^6 tonnes	% of year	Highest daily sediment load 10^6 tonnes
1969[a]	5.4	August	3.1	57	1.1
1970[a]	11.7	July	8.3	71	1.7
1971[a]	12.9	July	7.2	56	1.0
1972[a]	9.4	June	4.5	48	0.7
1973[b]	8.2	June	5.4	66	0.8
1974[b]	6.0	July	2.5	42	0.3
1975[b]	5.3	July	2.3	43	0.3
1976[c]	3.3	August	1.1	33	0.1
1977[c]	5.5	June	2.4	44	0.3
Average	7.5				
Standard deviation	3.2				

[a] Based on data for Athabasca River below Fort McMurray.

[b] Based on data for Athabasca River at Fort McMurray plus Clearwater River at Draper.

[c] Based on data for Athabasca River at Embarras.

Measurements of the distribution of sediment between the four main delta distributaries are limited to about a dozen specific dates in 1973 and 1975. As might be expected, these data indicate that the distribution of sediment tonnages among the four channels is not substantially different from the distribution of flow volumes indicated by Figure 7. On a day-to-day basis, there appear to be notable differences between total sediment tonnages in the delta channels and in the river below Fort McMurray, even allowing for travel times.

The average distribution of annual sediment inflow by months is indicated in Table 6. Year-to-year variations in the distribution are quite large; for example, the proportion of the annual total carried in June has varied between 7% and 64%, and the proportion in September between 1% and 25%. Figure 9 shows through-the-year sequences of daily sediment inflow for three different years.

Measurements of suspended sediment in the outflows from Lake Athabasca are limited to a number of specific dates in 1973, 1975 and 1976. An attempt was made to fill in these data with the aid of discharge and water level data, to give an indication of total sediment outflow to the Slave River. Results are indicated in Table 7. It appears that annual sediment outflow may amount to approximately 65% of annual sediment inflow. Over shorter periods it appears that sediment outflow may occasionally exceed inflow. For example, reported data indicate a sediment outflow rate, during the second half of May 1976, of approximately 15 000 tonnes per day, whereas reported inflow rates (Embarras data) over the same period were only about 50% of this figure.

Sediments in the outflow channels from Lake Athabasca are considerably finer than those in the Athabasca Delta distributary channels, as might be expected. Grain size data from samples taken in the inflow and outflow channels are shown in Table 8.

A check was run on the sediment balance figures quoted in Table 7 by considering the change in grain size distributions

Table 6. Distribution of Athabasca River sediment by months.

Month	Percent of total for season (1969-77)	Percent of total for year (1970-72)	Estimated % of total for year (1969-77
January	-	negligible	negligible
February	-	"	"
March	-	"	"
April	-	6	6
May	16	12	15
June	28	32	26
July	34	46	32
August	16	3	15
September	6	1	6
October	-	negligible	negligible
November	-	"	"
December	-	"	"
Totals	100	100	100

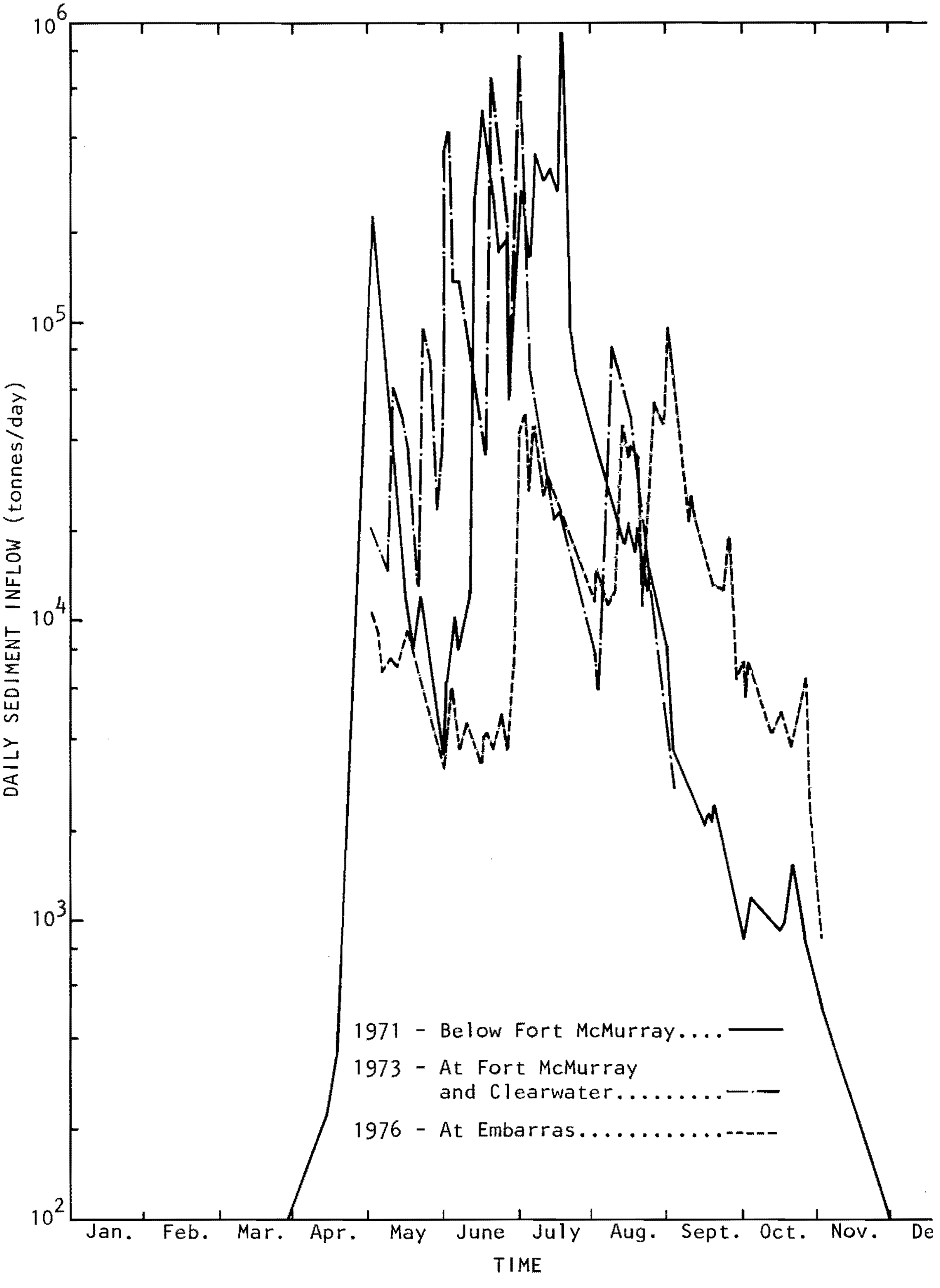


Figure 9. Sequences of daily sediment inflow from the Athabasca River for 1971, 1973, and 1976.

Table 7. Inflow vs. outflow of sediment for Lake Athabasca.

Year	Sediment inflow[a] 10^6 tonnes	Estimated sediment outflow 10^6 tonnes	Outflow[b] as percentage of inflow
1973	8.2	6.5	79
1975	5.3	2.9	55
1976	3.3	2.0	61
		Mean	65

[a] Based on Water Survey of Canada data for Athabasca River quoted in Table 5.

[b] Based on Alberta Environment data for Riviere des Rochers. No allowance is made for other outflows, to compensate for non-accounted inflow sources.

Table 8. Grain size constitution of sediments.

Source	Percent finer than (mm)									Median dia.
	.002	.004	.008	.016	.031	.062	.125	.25	.5	(D_{50}) mm
Athabasca River, suspended sediment[a]	16	24	38	54	68	81	91	97	99	0.014
Delta distributary channels, bed load										0.08 to 0
Riviere des Rochers, suspended sediment[b]										0.006
Riviere des Rochers, bed load										0.01 to 0

[a] Average of 77 samples at Embarras and Fort McMurray, 1969-77; highly consistent.

[b] Average of 8 samples in 1973 only.

between suspended sediments in inflow and outflow. The median grain size of outflow sediments appears to average about 0.006 mm (in the fine silt range); that is, 50% of the outflow tonnage is finer than 0.006 mm. Since about 30% of the inflow tonnage is finer than 0.0006 mm (Table 8) it can be inferred that total outflow tonnage represents approximately 60% of inflow tonnage, provided that material finer than 0.006 mm does not settle out significantly. This is in reasonable agreement with the average result shown in Table 7.

If it is assumed that 65% of Athabasca River sediment passes through to the Slave River, then, on the basis of Table 5, sediment retained in the Delta averages about 2.6 million tonnes per year. Assuming a density of 1600 kg/m^3 and an average deposition thickness of 3 m, this would mean that the Athabasca Delta is extending areally by about 0.8 km^2 per year. A comparison of delta shorelines as indicated by (i) National Topographic map based on airphotos of 1955-58, and (ii) LANDSAT image of 22 June 1980, indicates that in fact the delta has advanced by approximately 1 km over a front of approximately 20 km in the last 24 years or so: an average rate of approximately 0.8 km^2 per year. According to Bayrock and Root (1973), however, the average rate of areal growth over the last 10 000 years has been about 0.2 km^2 per year. This is an important discrepancy, to explain which a number of hypotheses might be advanced. The most likely seems to be that the sediment inflow is considerably greater at present than it was over most of the last 10 000 years, probably as a result of agricultural settlement over substantial parts of the Athabasca drainage basin in central Alberta.

3.5 BOTTOM TOPOGRAPHY AND MATERIALS

Figure 10 shows bottom contours of Lake Athabasca in the area of interest, also those of Lakes Claire and Mamawi. At an average Lake Athabasca water level of 209.3 m, the maximum depth between Bustard Island and the delta shoreline is approximately 4 m

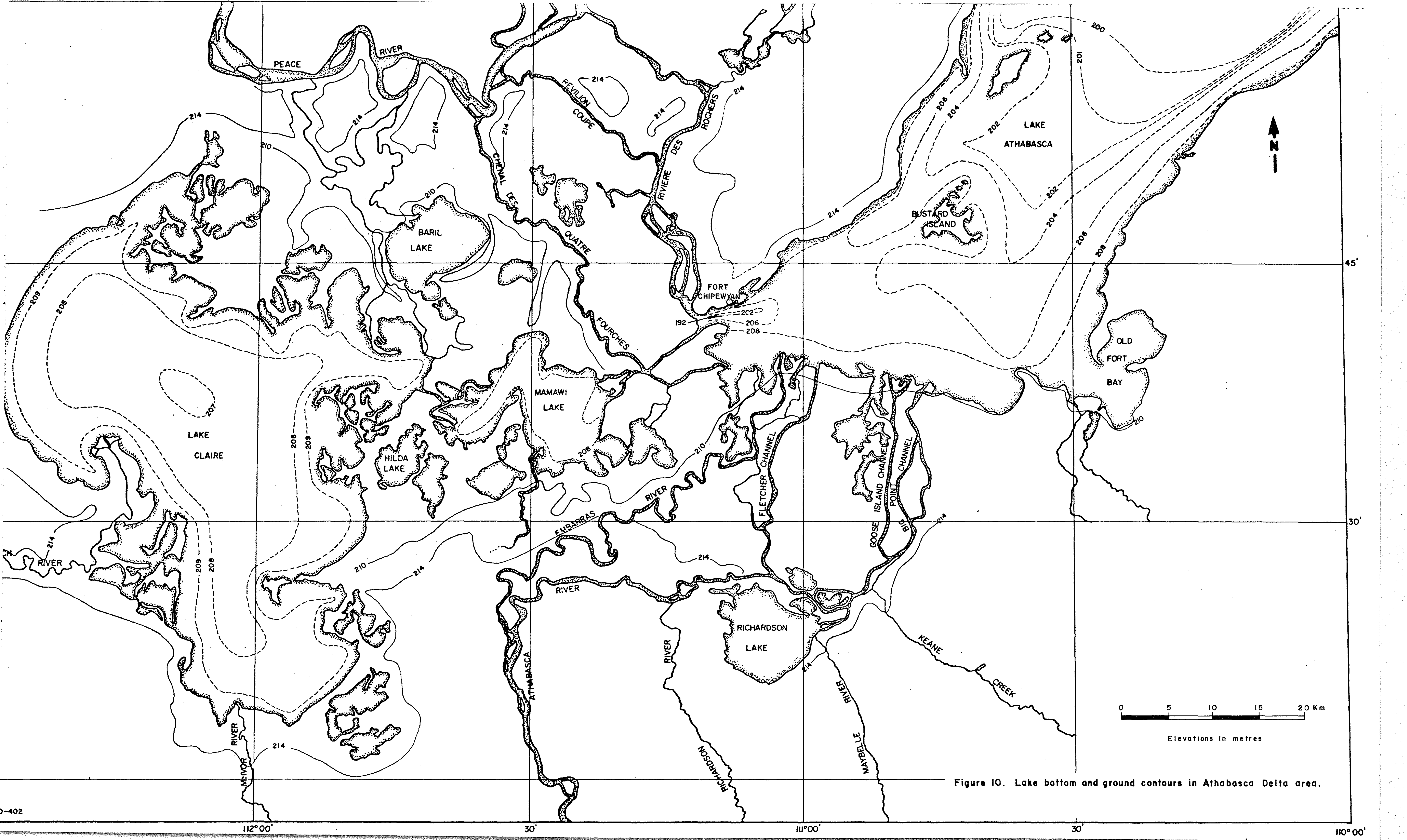


Figure 10. Lake bottom and ground contours in Athabasca Delta area.

except for a 500 m wide channel leading to the lake outlet; this begins about 8 km east of the actual head of the Riviere des Rochers and is up to 15 m deep. In the area within which most of the circulation and mixing of the Athabasca River inflow apparently occur, which extends not more than about 10 km from the delta shoreline (see Section 4), the mean depth under average lake level conditions is only about 2 m. The volume of this part of the lake, within which most of the inflow circulation occurs, is in the order of 0.4 km^3. For an average open-water inflow of 1200 m^3/s, the average retention period is therefore in the order of 4 days.

Lake Claire is mostly about 1.5 to 2 m deep, and Mamawi Lake is about 1 m deep, under average water levels.

A certain amount of data is available on bottom sediments in Lake Athabasca and Lake Claire. Figure 11 shows percentages of sand in samples from the bottom of Lake Athabasca in the delta area (Bayrock and Root, 1973), the balance of the samples being silt and clay. The percentage of sand drops to negligible proportions at roughly 5 km from the delta shoreline, except opposite Big Point channel where sand extends to about 8 km.

3.6 ICE AND WIND CONDITIONS

The mean date of first permanent ice on Lake Athabasca at Fort Chipewyan is 23 October, and the mean date for the lake to be ice-free is 29 May (Allen, 1977). The range of year-to-year variation extends about 2 weeks on either side of these dates.

Maximum ice thickness at Fort Chipewyan varies from 0.6 to 2.0 m with a mean value of 1.1 m (Allen, 1977). As shown previously (Figure 8), the ice cover has an erratic effect on lake outflow via the Riviere des Rochers.

A number of ice-related phenomena are significant in relation to distribution and circulation in the delta area. Historically, ice jamming on the Peace and Slave rivers often restricted the outflow from the lake and caused water from the Peace to flood the Delta. The channels connecting Lakes Claire and Mamawi

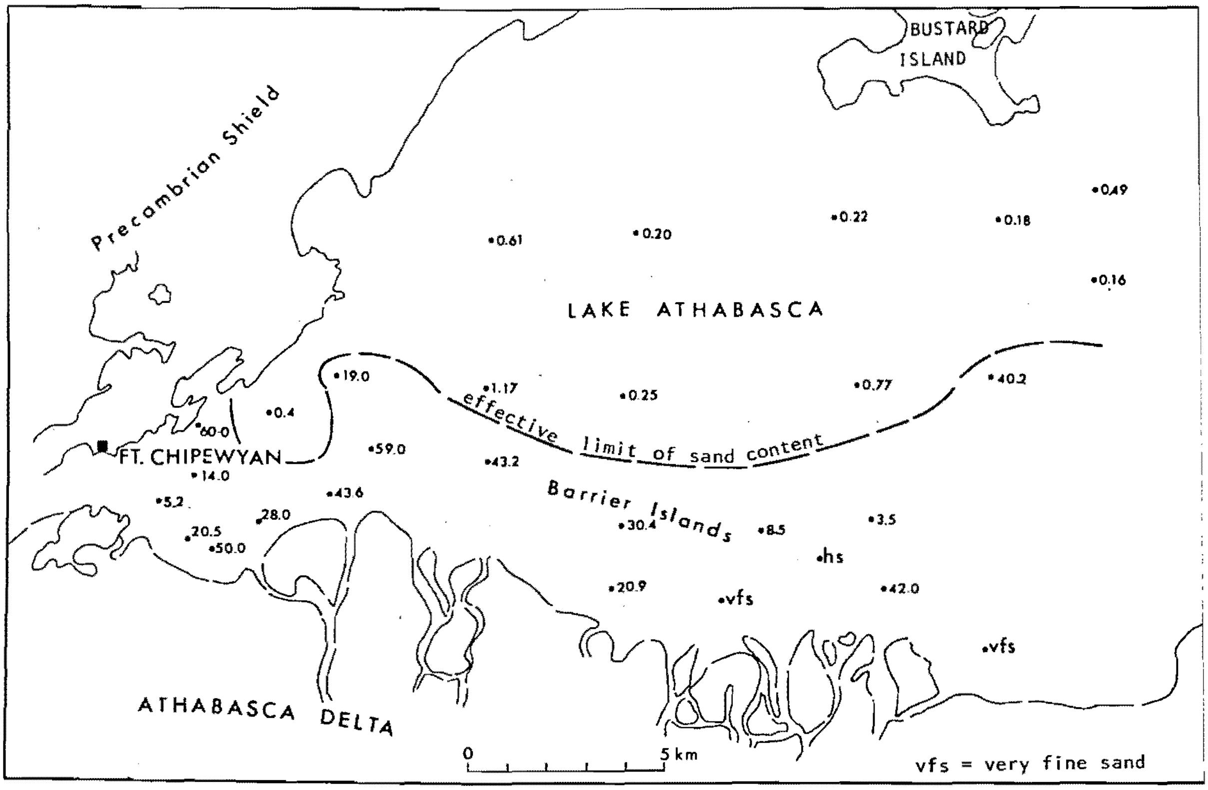


Figure 11. Percentage of sand in bottom samples from Lake Athabasca (based on Bayrock and Root 1973).

to Lake Athabasca can freeze solid during the winter months. In Lake Athabasca, ice formation in the shallow part of the lake east of Fort Chipewyan and north of the Embarras River mouth (Figure 10) restricts the outflow: winter water level records for Fort Chipewyan show that in some winters local water levels were considerably lower than in the main body of the lakes, particularly in the 1969-72 period when lake levels were particularly low. Since completion of the control weirs in 1976, this phenomenon has not recurred.

Wind 'set-up' can cause noticeable day-to-day fluctuations in the water level of Lake Athabasca, particularly when winds are oriented with the northeast-southwest axis of the lake. Figure 12 shows that a 21 km/h wind from the north-northeast on 26 August 1976 raised the lake level at Fort Chipewyan by nearly 0.4 m above the prevailing level. The overall effect of this phenomenon on the hydrology of the system is to increase the outflow of Lake Athabasca. Conversely, when a strong wind blows from the southwest, a drop in water level occurs near the outlet and the ouflow temporarily decreases. On 3 September 1972 a 32 km/h wind from the west lowered the water level at Fort Chipewyan by 0.8 m (Peace-Athabasca Delta Project 1973).

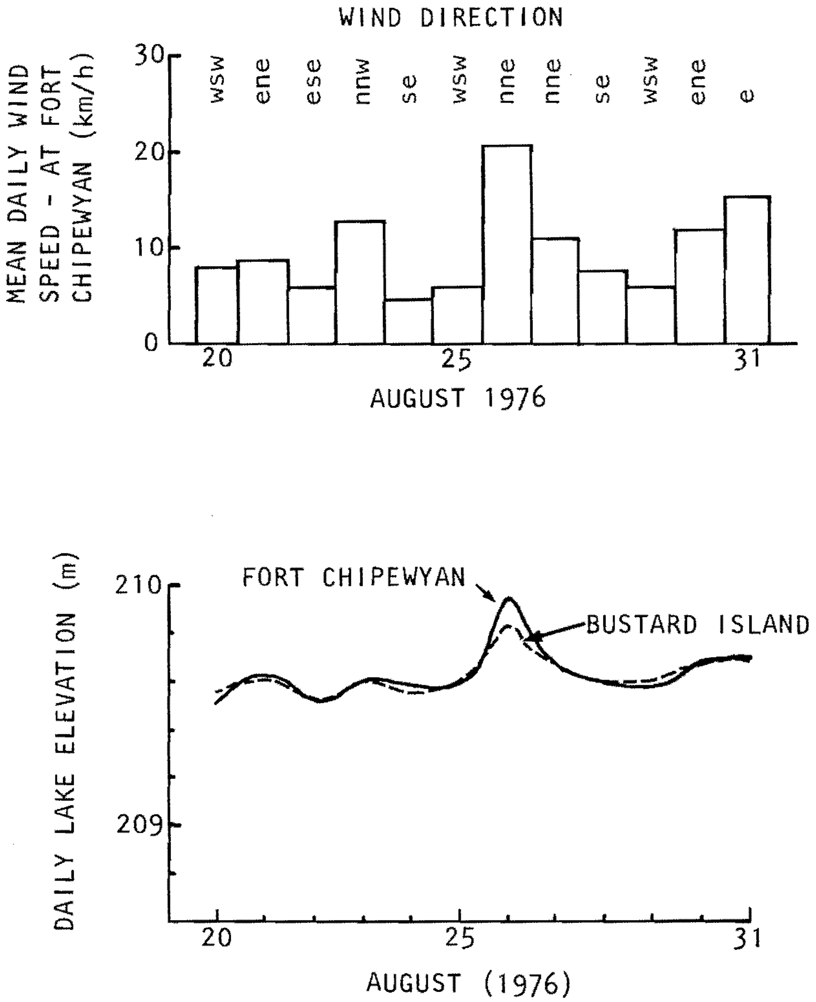


Figure 12. Effect of wind on water levels at southwest end of Lake Athabasca.

4. INFORMATION FROM PASSIVE REMOTE SENSING

4.1 USE OF SATELLITE AND AERIAL PICTURES TO STUDY WATER AND SEDIMENT

Before discussing remote sensing information on the Athabasca Delta area, salient aspects of interpreting water and sediment patterns from satellite images and aerial photography will be reviewed. Standard references on remote sensing include American Society of Photogrammetry (1975), U.S. Geological Survey (1976), and Lintz and Simonett (1976).

4.1.1 Basic Concepts

In order to interpret remotely sensed data correctly, the electromagnetic energy interactions that produce this data should be understood. Images of a water body produced by cameras or non-optical scanners depend upon the amount of energy reaching the sensor by reflection or emittance from the water body. This energy may be in the form of visible light, as in the case of reflected sunlight, or in other forms including thermal infrared radiation emitted by the water surface due to its temperature.

Figure 13 shows a simplified view of energy relationships pertinent to remote sensing of suspended sediment. First there is radiant energy emitted by the sun, so-called solar or short-wave radiation with wavelengths from 0.1 to 4.0 m. This consists approximately of 10% ultraviolet (0.1 to 0.4 m), 45% visible (0.4 to 0.7 m) and 45% infrared (0.7 to 4.0 m). Of the incident solar radiation that reaches the water surface, part is reflected, part is absorbed by the water, and part is transmitted through the water. The proportion allocated to each route is dependent on wavelength and also on water properties. Some dissolved materials absorb certain wavelengths of light: tannic acid, for example, absorbs energy from blue light and results in a reddish-brown color.

The reflected energy picked up by the sensor is made up of three components: (i) reflected energy from the water surface; (ii)

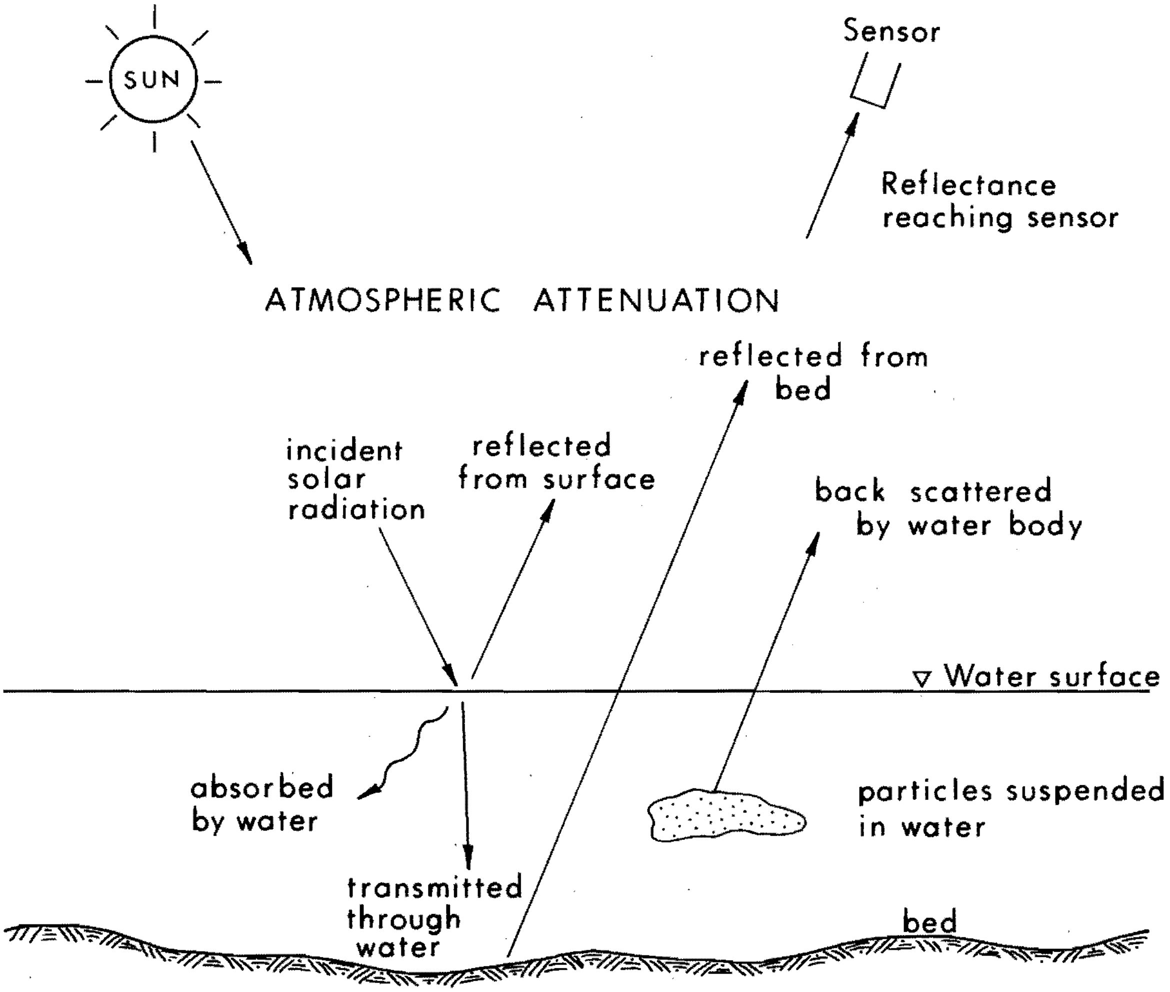


Figure 13. Energy relationships in remote sensing of water and sediment.

energy transmitted through the water body and reflected from the bottom; and (iii) backscattered energy reflected off suspended particles. Theoretically, the larger the concentration of suspended particles, the greater the backscattered component and the greater the reflectance recorded by the sensor. Figure 14 shows a typical experimental relationship.

An important consideration in interpreting the signal received by a sensor is the depth to which energy can be transmitted before being extinguished. A signal will be reflected from the bottom if the transmitted energy is not totally extinguished before reaching the bottom. Characteristics of the bed will then be included in the total signal received by the sensor, and may hinder interpretation of the suspended sediment pattern. Even if the energy is extinguished before reaching the bottom, knowledge of the extinction depth is important. For example, if there is a strong gradient of sediment concentration with depth, energy will tend to backscatter off the upper layer of suspended particles only, resulting in an incorrect indication of the average concentration. For visible light, the extinction depth is essentially the same as the Secchi depth index commonly used in water transparency evaluation, whereby transparency is related to the visibility limit of a white disc submerged in the water.

The depth to which energy is transmitted depends on the wavelength of the energy and on the concentration and type of suspended material. Figure 15 shows relationships for five different water sources, from an experimental study by Scherz and Van Domelen (1975). For distilled water, maximum light penetration occurs for a wavelength of approximately 0.48 m. Only 10% of the light energy penetrates below a depth of 55 m, which is the theoretical Secchi depth.

Turbidity, being an optical property, correlates better than sediment concentration with the amount of reflectance received by a sensor. Only where turbidity is highly correlated with sediment concentration will there be a reasonable correlation

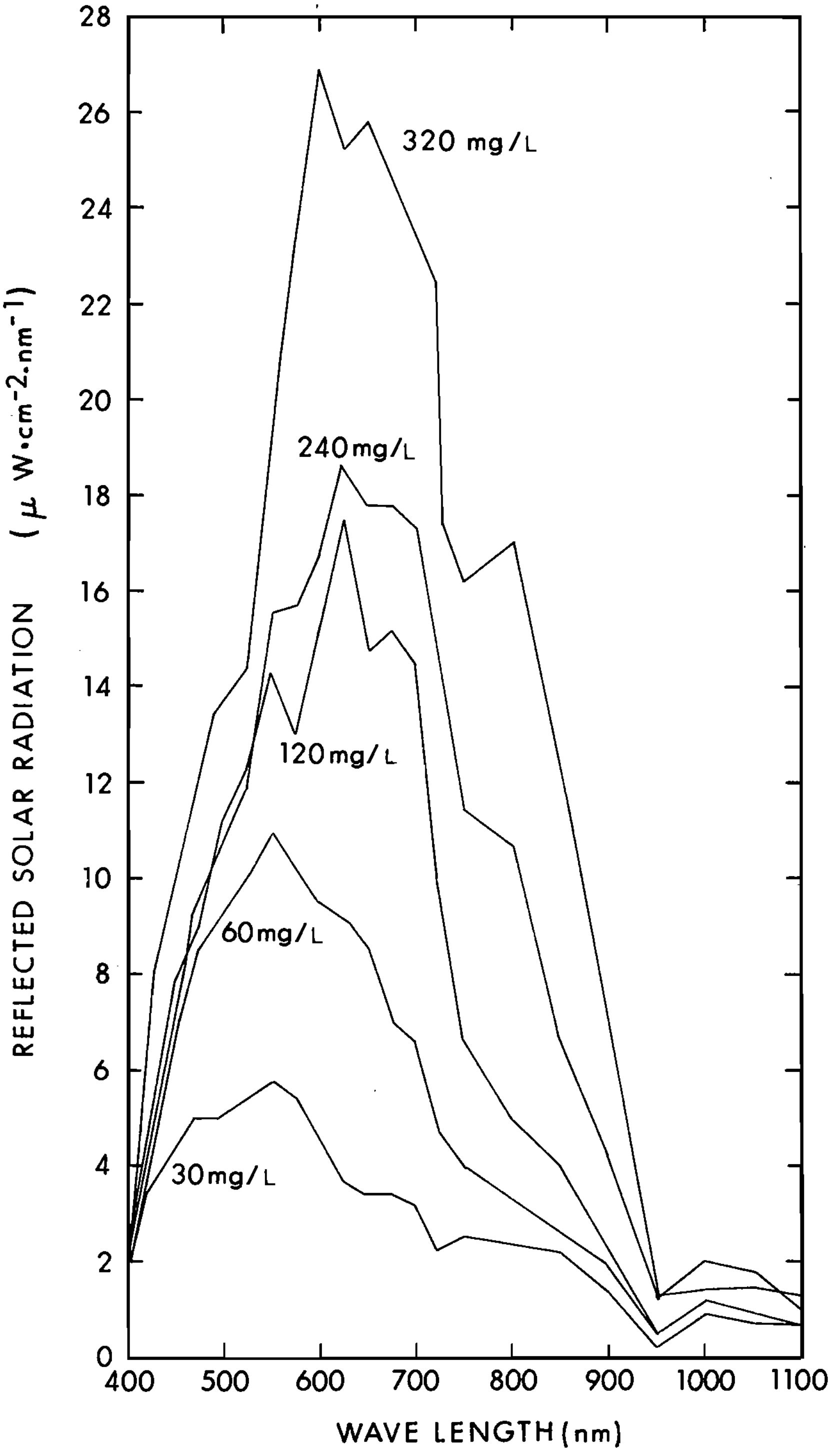


Figure 14. Typical experimental relationship between reflectance, energy wavelength, and sediment concentration (Ritchie, Schiebe and McHenry 1976).

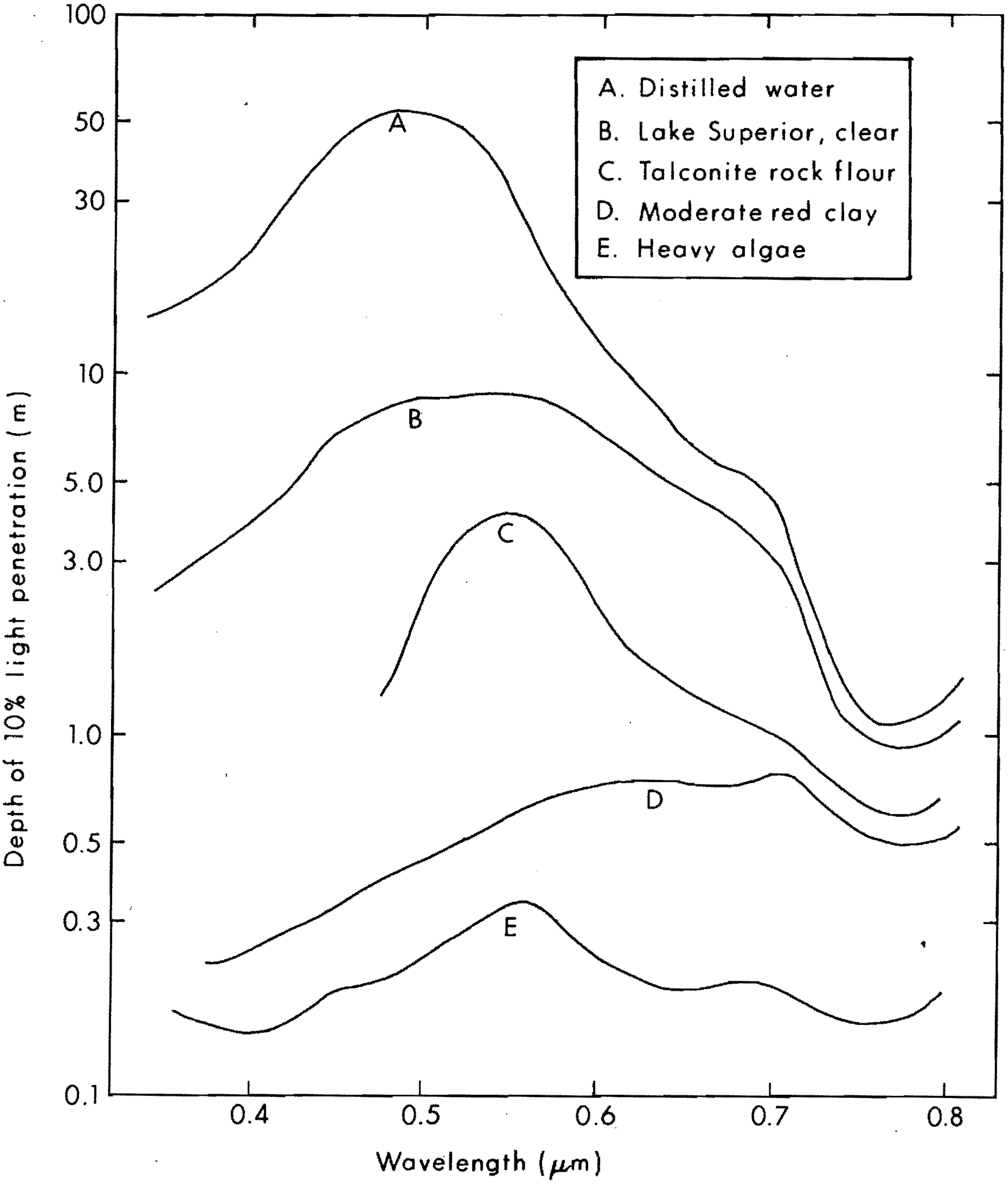


Figure 15. Experimental relationships between penetration depth and energy wavelength for various clear and turbid waters (Scherz and van Domelen 1975).

between measured reflectance and sediment concentration. The question of quantitative interpretation of reflectances in terms of sediment concentrations is discussed further in Section 7.3.

4.1.2 LANDSAT Imagery

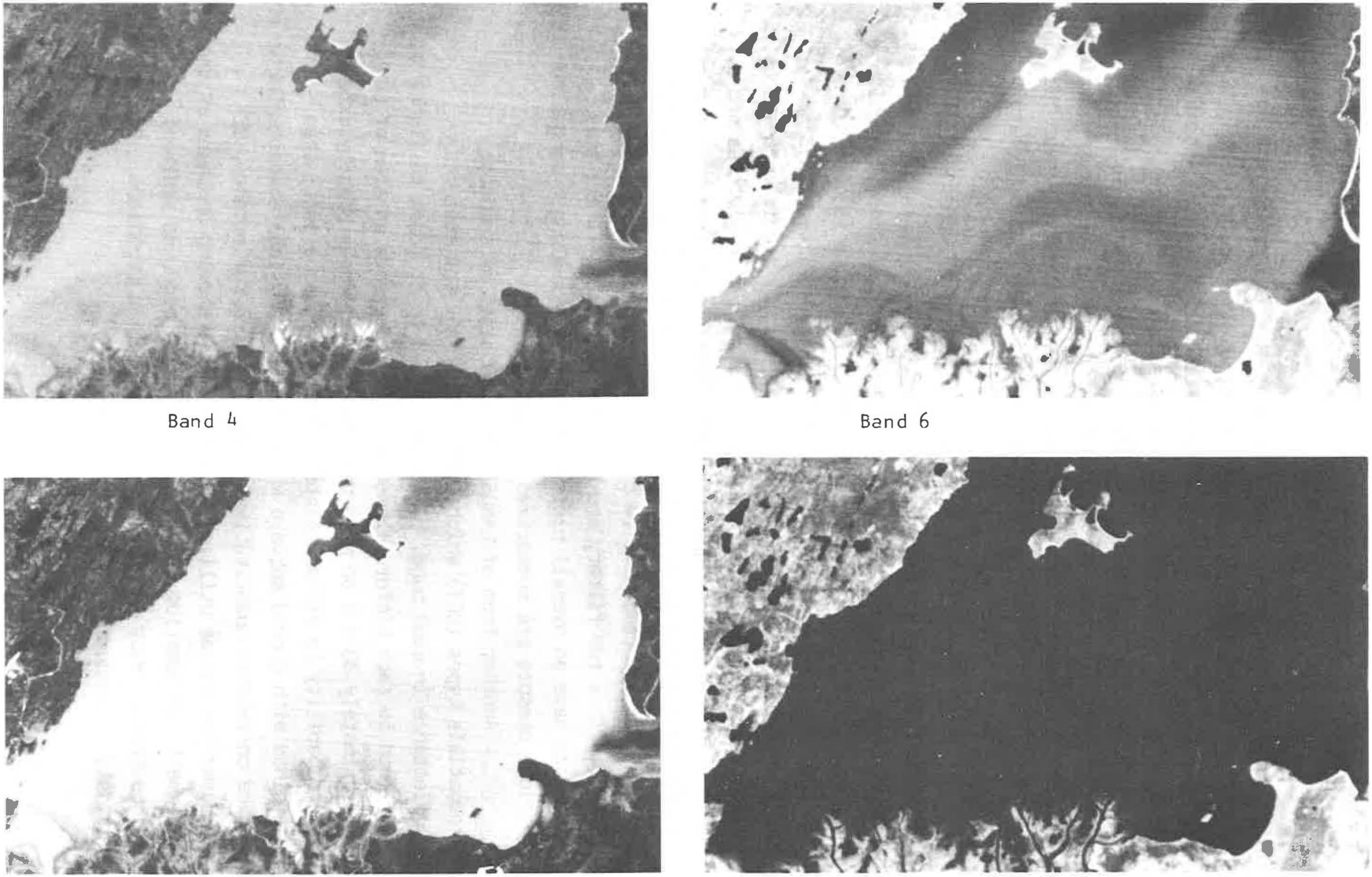
The most useful wavelength range for detecting sediment is from 0.4 to 0.8 m; this range comprises the visible (0.4 to 0.7 m) and part of the infrared. The LANDSAT (previously ERTS) satellites, using a multispectral scanner (MSS), receive most of this range in the form of three separate signals: Band 4 (0.5 to 0.6 m, visible), Band 5 (0.6 to 0.7 m, visible) and Band 6 (0.7 to 0.8 m, 'near' infrared). They also receive an additional infrared range as Band 7 (0.8 to 1.1 m). As indicated by Figure 14, maximum reflectance of the higher concentrations occurs in the Band 5 range: one might therefore expect Band 5 to be the best single MSS band for detecting suspended sediment in water bodies of significant depth. This has been the experience in a number of studies (for example, Bartolucci et al. 1977; Klemas et al. 1973; Bukata and Briton 1974).

The interactions of radiant energy with the water are different in the four MSS bands. The energy in the infrared Bands 6 and 7 is mostly absorbed in the uppermost few centimetres of water. Band 7 has a penetration depth of only 1 mm in clear water (Alfoldi 1974) and unless there is material such as algae on the surface of the water, the sensor receives no reflected signal in this band and the water appears black. This infrared band is therefore the most useful for delineating land-water boundaries. Band 6 has a greater penetration and is useful for detecting near-surface suspended solids. The depth-penetrating abilities of Bands 4 and 5 vary with the amount and type of suspended material in the water, as can be seen in Figure 15. For example, Bartolucci et al (1977) indicate that with a suspended concentration of 100 mg/L the depth of penetration is only about 30 cm. In a sediment-laden tidal inlet, Thomas (1978) found the penetration depth of Band 5 to be 45 to 50 cm and that of Band 6 to be 15 to 20 cm.

As an example, Figure 16 shows the four spectral bands for a single LANDSAT scene of the Athabasca Delta area on 22 June 1980. Bands 4, 5 and 6 show a very distinct area of suspended sediment extending from the delta shoreline out to Bustard Island. Band 5 shows the brightest reflectance in the form of very light grey tones. Band 6 shows patterns in darker tones but with more distinct banding,indicating that susp~~s~~ended sediment occurs very near the surface. Band 7 shows only a very faint pattern but delineates the lake boundary very clearly.

The pictorial products available from a LANDSAT image include black-and-white pictures for each of the four MSS bands, as exemplified in Figure 16, plus two types of color composite which combine three of the four bands. The C1 composite is composed of Band 4 with a blue filter, Band 5 with a green filter and Band 7 with a red filter, and tends to have an overall reddish appearance. Clear water bodies appear black in the single band pictures and dark blue on C1 composites, and water with increasing concentrations of suspended material produces lighter grey or blue tones. The less common C2 color composite is composed of Band 5 with a green filter, Band 6 with a red filter, and Band 7 with a blue filter; these pictures have an overall bluish appearance. Wavelength ranges for various sensors are summarized in Figure 17.

Another form of LANDSAT data consists of computer compatible tapes (CCT) which record digitally the measured reflectance in each band. An index from 0 to 63 (dark to light) is assigned to each picture element, which represents an area of approximately 80 m x 80 m on the ground. The tapes greatly extend the capability to differentiate reflectance over a small area. If combined with ground surveys which enable a physical characteristic to be correlated quantitatively with measured reflectance, CCT information can be utilized to produce maps showing contours of the parameter in question. Klemas et al (1973) produced sediment concentration maps for Delaware Bay using this technique. This form of data is discussed further in Section 7.3.



Band 4

Band 6

Band 5

Band 7

Figure 16. Comparison of MSS Bands 4, 5, 6 and 7 for southwest end of Lake Athabasca, 22 June 1980.

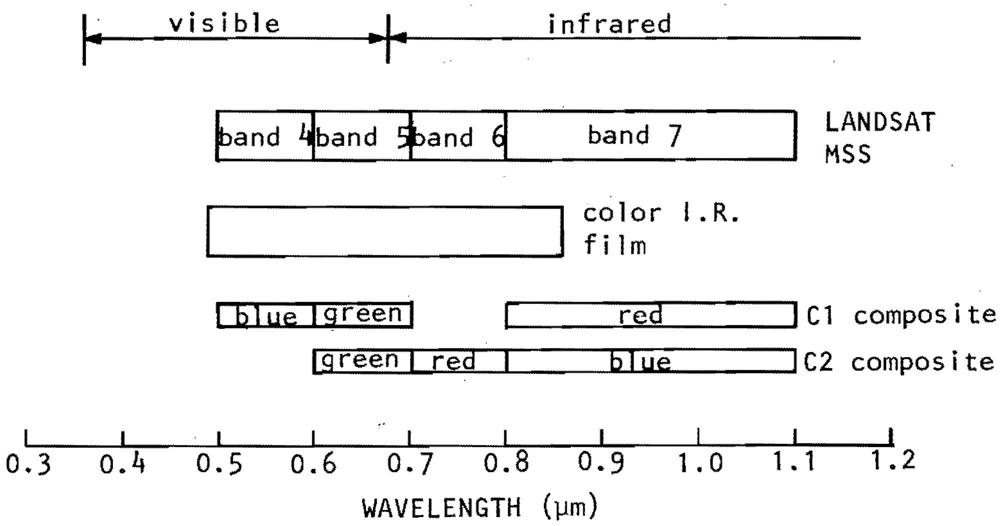


Figure 17. Energy wavelength ranges for various sensors. Based on Lintz and Simonett, 1976.

4.1.3 Aerial Photography

In addition to satellite images, the present study has utilized aerial photographs taken on false-color infrared film. Used with appropriate filters, this film senses almost the same wavelength range as LANDSAT MSS bands 4, 5, 6 and 7 (Figure 17) and gives color renderings very similar to C1 composite images: green vegetation appears red, clear water appears dark blue, and sediment-laden water appears light blue.

4.2 SELECTED DELTA IMAGERY AND PHOTOGRAPHY WITH ASSOCIATED ENVIRONMENTAL CONDITIONS

A set of ten LANDSAT images at a scale of 1:500,000 was selected for preliminary interpretation, after a search had been made for listings of cloud-free images over the period 1973 to 1978. The basis for selection was to assemble a set of clear pictures representing a range of lake levels and inflow conditions.

Six of the pictures were obtained as C1 color composites formed from Bands 4, 5 and 7, while the other four were black-and-white pictures from Band 5. The essential difference between the two types with respect to water and sediment is that the C1 composite provides good depth penetration (because of Band 4) and clear delineation of water-land boundaries (because of Band 7), whereas the single-band 5 images provide somewhat less depth penetration and less clear distinction between land and water.

In addition to satellite imagery, color infrared aerial photography was procured from the National Air Photo Library for two dates. The first set, at a scale of approximately 1/100 000 from 1 and 2 July 1975, corresponds to C1 satellite imagery of the same dates and shows very similar color patterns. The second set, at a scale of approximately 1/56 000, is from 21 October 1977.

Table 9 lists dates of pictures and associated environmental conditions, including lake inflows and outflows, river suspended sediment concentrations, water levels, and wind conditions. Special comments about some of the data items in the table are given below:

River Flows

Athabasca River at Embarras represents the main inflow to Lake Athabasca in the delta area.

Fond du Lac River represents the largest non-delta inflow at the northeast end of Lake Athabasca. Other inflows around the lake, plus precipitation on the lake itself, account for approximately as much inflow as the Fond du Lac River, on an annual basis.

The difference between Peace River at Peace Point and Slave River at Fitzgerald represents mainly outflow from Lake Athabasca, principally via the Riviere des Rochers.

Lake Levels

Since 1975, loss of a temporary control weir on the Chenal des Quatre Fourches has prevented the level of Lake Mamawi from significantly exceeding that of Lake Athabasca.

Suspended Sediment Concentrations

This is available for Embarras since 1975 only. In the case of rapidly falling river flows, concentrations may have been much higher a short time previously.

Wind Conditions

Data given for Fort Chipewyan refer mainly to daylight hours. In many cases night winds are virtually zero. It is likely that winds on the lake are often considerably stronger than recorded at Fort Chipewyan.

Table 9. List of utilized satellite imagery and color aerial photography, with associated environmental data.

Date[a]	Type of picture[b]	River flows m³/s				Estimated outflow from L. Athabasca[d]	Water surface elevations m			Suspended sediment concentration mg/l		Wind conditions preceding 24 hrs - direction and max. speed km/h
		Athabasca at Embarras[c]	Fond du Lac	Peace at Peace Pt.	Slave at Fitzgerald		L. Athabasca at Ft. Chipewyan	Mamawi L.	Peace R.	Athabasca R.[e]	Peace R.[f]	
3 July 1973	Band 5	2180 (F)	320	4310	6120	1810	209.5	--	--	1040		Main E to SE Maximum 24
26 Aug 1973	C1 Composite	1240 (F)	310	2830	5160	2330	209.3	--	--	90		NW to SW Maximum 19
22 May 1974	C1 Composite	2050 (F)	280	6400	7590	1190	210.0	--	--	450	2000 (?)	E to S Maximum 23
2 Aug 1974	Band 5	1500 (F)	320	3090	6710	3620	210.2	--	--	110	200 (?)	Mainly calm
22 June 1975	Band 5	1180 (R)	410	3290	5010	1720	209.0	209.2	--	90	1090	Mainly E Maximum 23
1 July 1975	C1 Composite	2040 (R)	420	3120	4870	1750	209.0	209.2	--	660	2000 (?)	Mainly SW Maximum 27
2 July 1975	C1 Composite	2410 (R)	415	3260	4930	1670	209.0	209.2	208.6	1060		
1/2 July 1975	Color IR aerial (scale 1:100 000)											
9 Aug 1976	C1 Composite	1140 (R)	360	3570	5010	1440	209.4	209.3	208.9	220 (E)	100 (?)	SE to SW Maximum 16
1 Aug 1977	Band 5	1280	630	3120	5720	2600	209.9	209.7	209.2	90 (E)	100 (?)	Mainly E to N Maximum 27
21 Oct 1977	Color IR aerial (scale 1:56 000)	740	490	2050	4110	2060	209.55	209.4	208.1	20 (E)		Direction variable Maximum 45
13 Sept 1978	C1 Composite	2170 (R)	380	1590	3400	1810	209.2	209.1	207.3	300 (E)		S to SE Maximum 30

[a] Time of day is approximately 11 am for all LANDSAT pictures.

[b] Band 5 and C1 composite are LANDSAT images at scale 1/500 000.

[c] (F) and (R) indicate falling and rising flows respectively.

[d] Estimated as difference between Fitzgerald and Peace Point.

[e] (E) indicates data for Embarras. Other data are for Fort McMurray, 2 days before date of picture.

[f] (?) Indicates that figure was estimated from nearest available data.

4.3 INTERPRETATION OF SATELLITE IMAGERY AND AERIAL PHOTOGRAPHY

A preliminary description and interpretation of the tones and patterns seen on each of the pictures in Figures 18a to 18f is given below. Attempts are made to explain special features of each picture in terms of available data on environmental conditions.

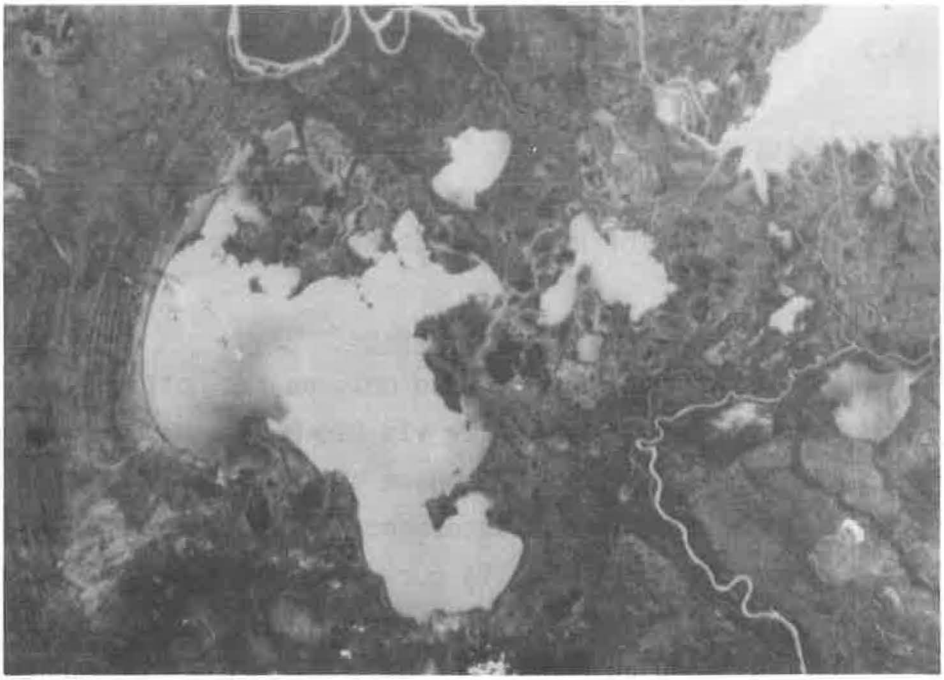
3 July 1973 - Band 5 Image

Lake Athabasca is seen only as far north as Bustard Island, and the main Athabasca inflow via Big Point channel is cut off. The visible portion of Lake Athabasca shows a fairly uniform light tone, with 'fingers' of darker water between the larger inflows. Inflows at the west end of the delta curve towards the lake outlet. Mamawi Lake and Lake Claire are also light.

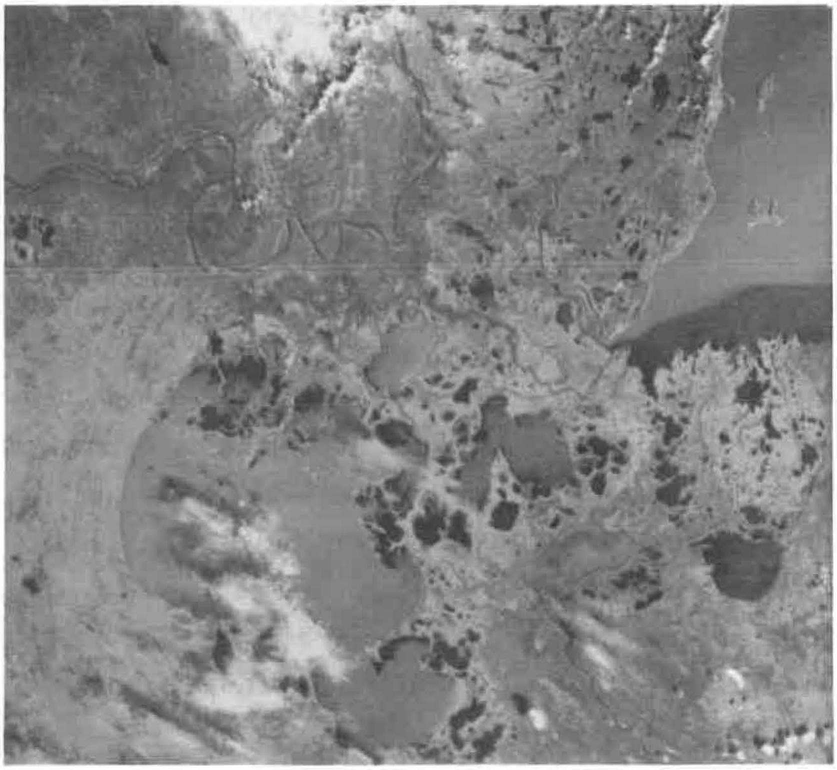
A flood with high sediment concentrations had peaked in the Athabasca River on 1 July, and winds were moderate from north to east for 48 hours previous. It is inferred that turbidity at the southwest end of Lake Athabasca was uniformly high because of both inflow and winds blowing along the length of the lake. The reason for the apparently high turbidity of Lakes Claire and Mamawi is not evident.

26 August 1973 - C1 Color Composite Image

This image is quite different from the previous one. The main portion of Lake Athabasca south from Burntwood Island is a uniform light blue color. A band of darker blue-grey water approximately 5 to 8 km wide extends out from the Athabasca Delta shoreline and is separated from the 'lake' water by a fairly distinct boundary. At the lake outlet, the darker water extends into the Chenal des Quatre Fourches but is not seen inside the Riviere des Rochers. Lake Claire is mostly light blue, like Lake Athabasca; Mamawi Lake is slightly darker. Sediment 'gyres' or rotational patterns are visible in Lake Athabasca north of Burntwood Island.

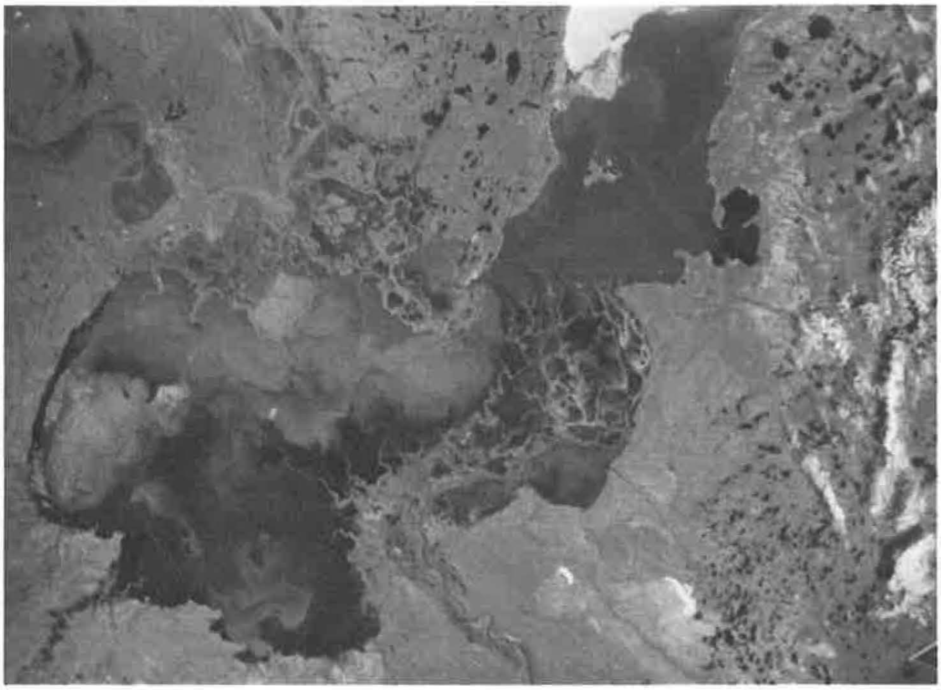


3 July 1973 Band 5

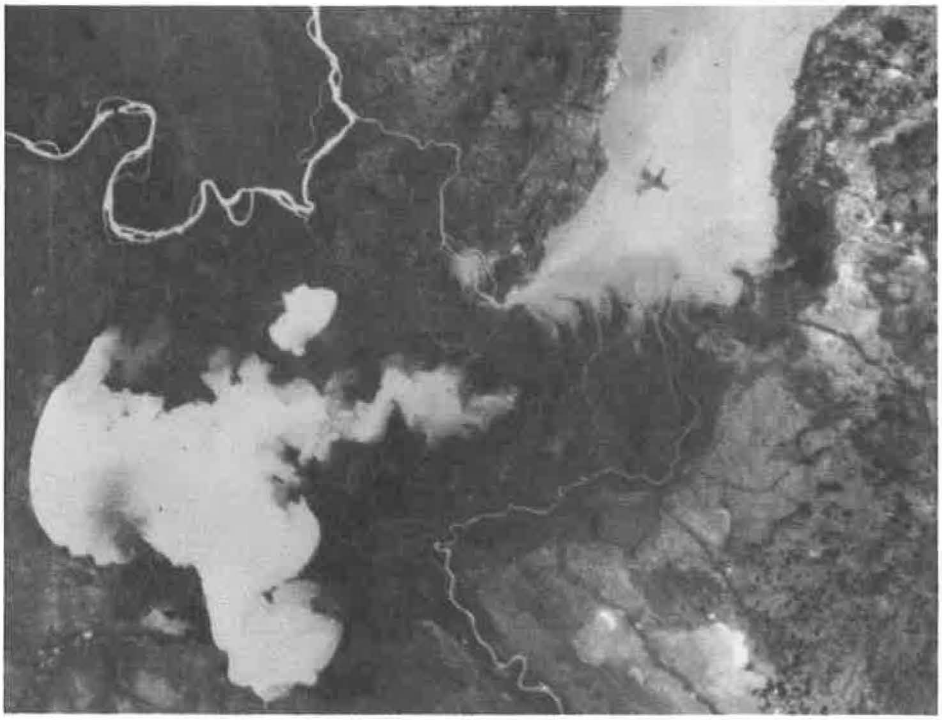


26 Aug. 1973 Cl Composite

Figure 18a. LANDSAT imagery and aerial photography 3 July and 26 August 1973.



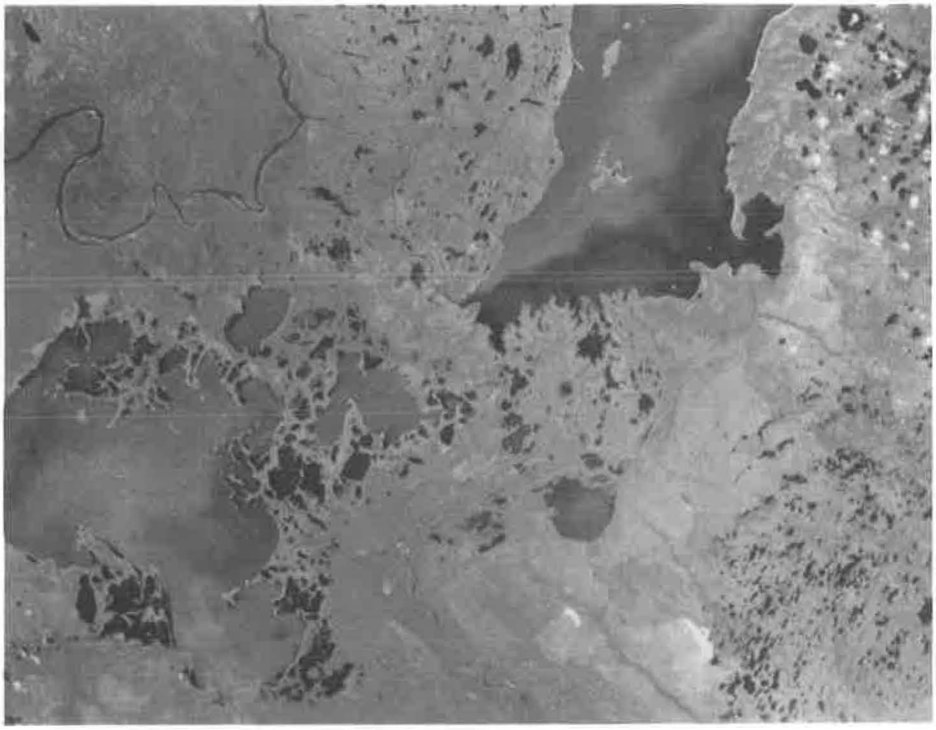
22 May 1974 C1 Composite



2 Aug. 1974 Band 5

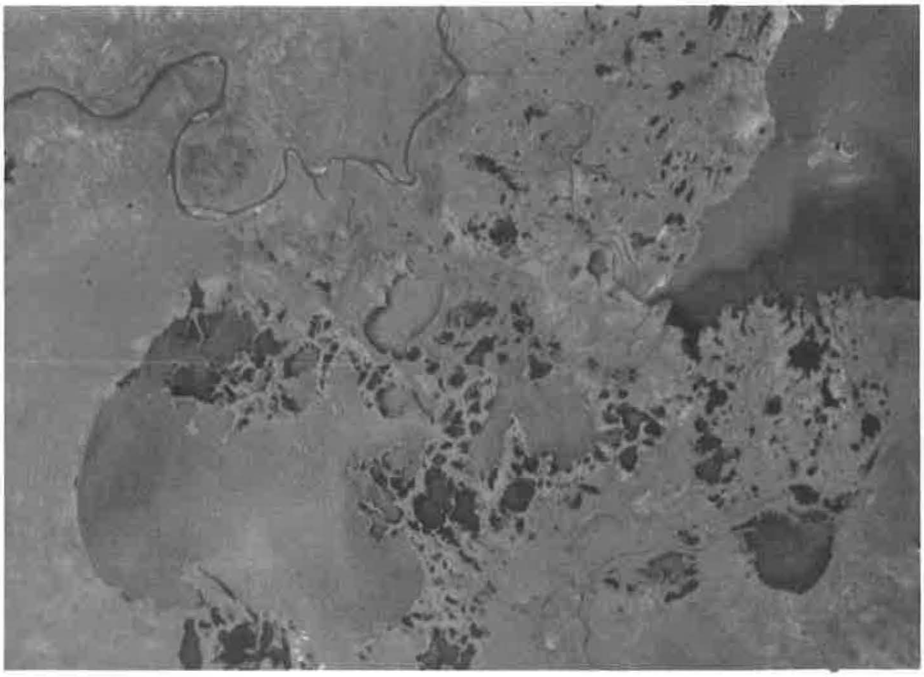
Figure 18b. LANDSAT imagery and aerial photography 22 May and 2 August 1974.

22 June 1975 Band 5

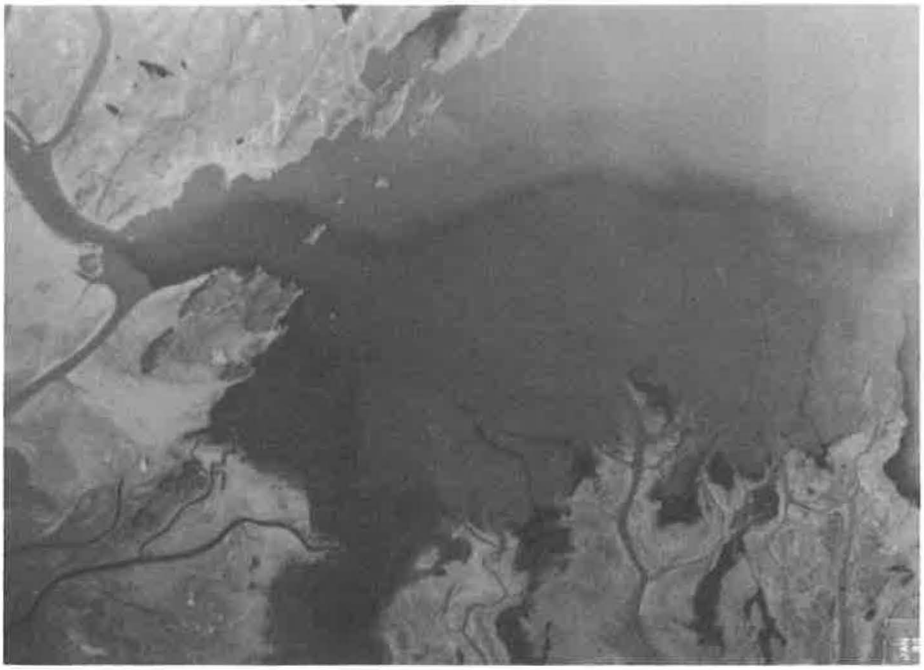


1 July 1975 C1 Composite

Figure 18c. LANDSAT imagery and aerial photography 22 June and 1 July 1975.



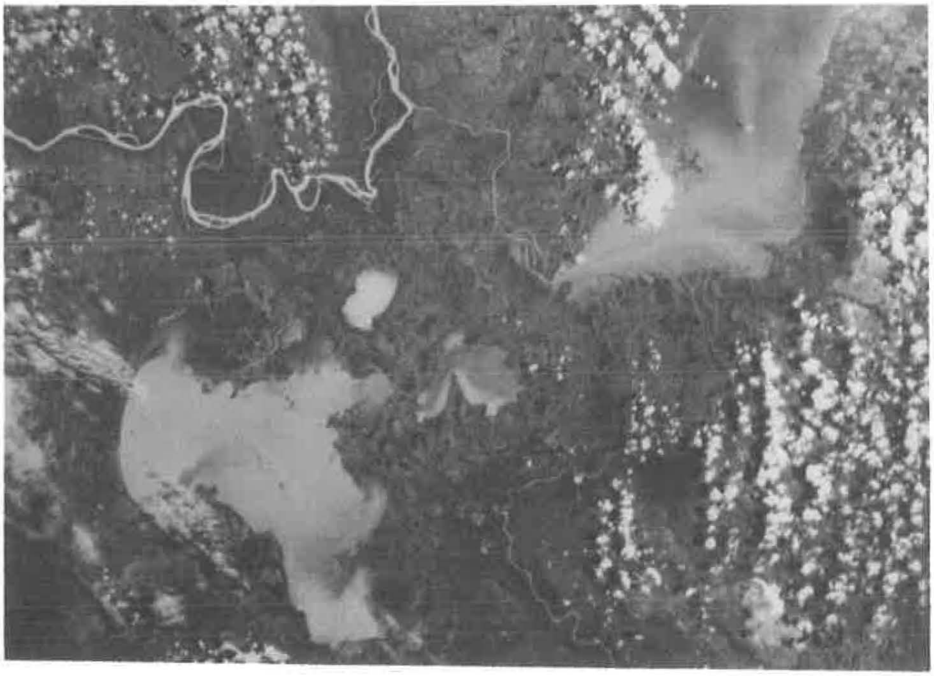
2 July 1975 C1 Composite



1/2 July 1975 Color IR Aerial

Figure 18d. LANDSAT imagery and aerial photography 1 and 2 July 1975.

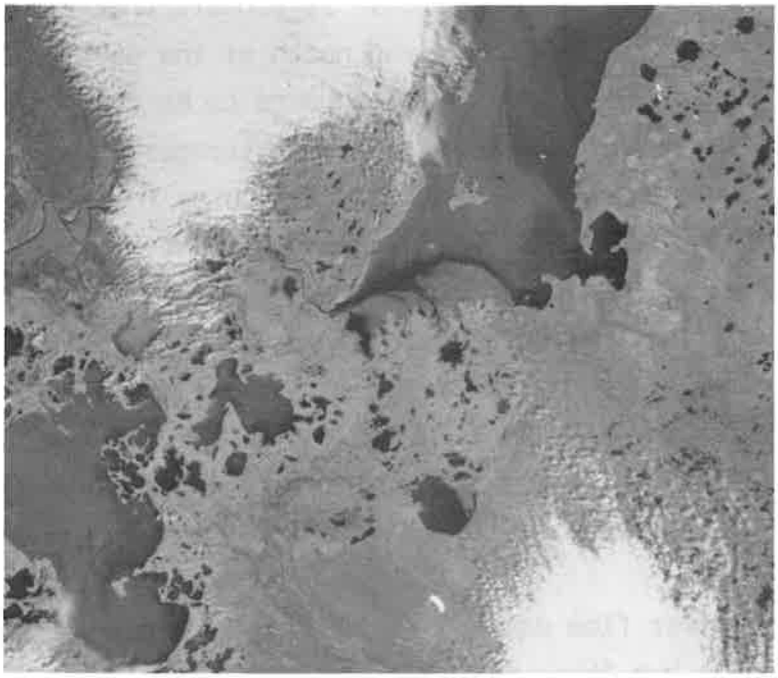
9 Aug.1976 C1 Composite



1 Aug.1977 Band 5

Figure 18e. LANDSAT imagery and aerial photography 9 August 1976 and 1 August 1977.

21 Oct. 1977
Color IR Aerial



13 Sept. 1978 C1 Composite

Figure 18f. LANDSAT imagery and aerial photography 21 October 1977 and 13 September 1978.

On this date Athabasca River inflow was apparently quite low in suspended sediment (Table 9), which may explain the darker water. The lakes may be light in color because of wind-induced wave-stirred sediment: winds had been moderate for the previous 24 hours. The reason for the apparent disappearance of river water at the outlet to Riviere des Rochers is not clear: either it is not being drawn into the outlet channel, or it is diving under the lake water. The fact that lake outflow considerably exceeded Athabasca River inflow may be significant. Dark streaks extending north from the delta shoreline may represent inflow of shallow groundwater and swamp water.

22 May 1974 - C1 Color Composite Image

This picture shows spring flood conditions, with ice in Lake Athabasca north of Burntwood Island and at the west end of Lake Claire. Most of the delta is under water and the three lakes form a continuous water body. Color tones in Lake Athabasca suggest moderate and fairly uniform turbidity. The boundary between 'river' and 'lake' water is indistinct: it appears that river water may extend nearly to Bustard Island north of the east part of the delta. Lake Athabasca outflow appears to be drawing mainly river water. Lakes Claire and Mamawi show stronger color patterns than Lake Athabasca, ranging from very dark blue (presumably clear water) near the south shore of Lake Claire to light grey-blue (presumably turbid water) near the north shore. The junction of greyish Peace River water with bluer Lake Athabasca water at the mouth of the Riviere des Rochers is clearly seen, and a boundary persists for about 10 km down the Slave River. The turbid water at the north side of Lake Claire and in Mamawi Lake is of similar greyish color to the Peace River, indicating that the Peace River was probably the source.

River flow data show that a spring peak of 2760 m^3/s occurred in the Athabasca at the end of April, and that flows oscillated at a generally high level through May. The Peace River peaked at 11 900 m^3/s, also at the end of April, and declined steadily through May. The extensive flooding and high lake level probably resulted mainly from the Peace River flood peak. Peak suspended sediment concentrations at the end of April had been approximately 1400 mg/L in the Athabasca and 3000 mg/L in the Peace. Wind mainly from the south and east may account in part for the greater turbidity of the north end of Lake Claire. Melting ice at the west end of Lake Claire appears to be associated with relatively clear water around the ice margins. The pattern at the Athabasca Delta front suggests that river water is curving to the left and entering the right side of the Riviere des Rochers, blocking out flow of lake water on this occasion: note the contrast from the previous picture.

2 August 1974 - Band 5 Image

Tonal contrasts are greater than in the previous Band 5 image of 3 July 1973, but land-water boundaries are difficult to distinguish. The reported level of Lake Athabasca is slightly higher than for 22 May and it is believed that approximately the same area is flooded. The main body of Lake Athabasca is lighter in tone than the river inflow area, and an indistinct water boundary occurs about 5 km north of the delta shore. The lake outflow, much higher than river inflow according to Table 9, appears to be drawing mainly lake water. As on 22 May, much of Lake Claire is of similar tone to the Peace River (white), but a darker area is evident around the Birch River delta. Old Fort Bay at the SE corner of Lake Athabasca is totally clear.

The Athabasca River peaked at 2890 m^3/s on 18 July and declined thereafter. The Peace River peaked at 4960 m^3/s on 24 July and declined thereafter. It appears likely that most of the turbidity seen in the picture resulted from high inflows rather than from wind-wave effects, but the reason for turbidity in the north part of Lake Athabasca is not obvious.

22 June 1975 - Band 5 Image

This picture is different from previous Band 5 images in that the main part of Lake Athabasca is dark, suggesting clear water. Athabasca River inflow appears less turbid than in the previous picture of 2 August 1974, although suspended sediment data for Fort McMurray (Table 9) indicate similar concentrations. In contrast to Lake Athabasca, Lakes Claire and Mamawi appear uniformly light, as does the Peace River. The Peace River, however, does not appear as light as on 2 August 1974, although the reported sediment concentration is greater. There is a fuzzy boundary between river inflow and lake water about 5 km north of the delta shoreline, and it appears that river water is swinging left to enter the Riviere des Rochers. Water is flowing out of Mamawi Lake into the Peace River and Lake Athabasca via Chenal des Quatre Fourches. There appears to be a narrow current of lake water flowing southwest along the Fort Chipewyan shore and into the Riviere des Rochers.

Flows in the Athabasca and Peace Rivers had been relatively steady since late April. Sediment concentrations in the Athabasca had declined to about 100 mg/L, from about 500 mg/L at the beginning of May. The turbidity around Bustard and Burntwood Islands may be due to wind from the east. The reason for the uniform turbidity of Lakes Claire and Mamawi (in contrast to the Cl composite of 22 May 1974) is not obvious, but may also be a result of wind. Richardson Lake, southeast of the Athabasca Delta, appears comparatively clear.

1 and 2 July 1975 - Cl Color Composite Images and Color Infrared Aerial Photography

All three pictures are very similar. Lake Athabasca, of which an 80 km length can be seen in the 2 July image, somewhat resembles the Band 5 picture of 22 June, but turbidity patterns are more extensive. Lakes Claire and Mamawi show more patterns, and the Peace and Athabasca Rivers do not appear as light in tone as parts of the lakes, although sediment data indicate high concentrations. There is a complex boundary between river inflow and lake water 5 to

10 km north of the delta shoreline, with a band of dark water between lighter inflow to the south and even lighter lake water to the north. Red streaks inshore of the boundary indicate weed growth at the water surface. The aerial photographs show clearly that at the lake outlet to Riviere des Rochers, a thread of darker (Athabasca River) water passes into the middle of the river channel, with lighter Lake Athabasca water on the right bank and lighter Mamawi Lake water from the Chenal des Quatre Fourches on the left bank.

Comparison of the LANDSAT images of 1 and 2 July shows notable changes over a 24 hour period. The boundary off the east part of the delta has pushed out by about 2 km and become less distinct, probably as a result of rising flows in the Athabasca River (which peaked for the year on 4 July). Wind from the southwest, causing mixing in the lake, may also be a factor. Less obvious changes can be detected in color patterns in Lakes Claire and Mamawi, presumably due to wind.

'Fingers' of dark water extend out from the delta shoreline between the turbid inflows; these appear to be boundary zones of clear water originating from shallow groundwater or swamp areas. Note that in contrast with the Band 5 pictures of 2 August 1974 and 22 June 1975, the delta patterns do not show strong curvature towards the lake outlet, probably because lake outflow is relatively smaller in relation to inflow (Table 9). The momentum of the inflow may be a factor in this pattern.

9 August 1976 - C1 Color Composite Image

Lake Athabasca is turbid along the northwest side but clear to the north and east, more or less as on 22 June and 1/2 July 1975. Lakes Claire and Mamawi, and the Athabasca and Peace rivers, appear turbid. The boundary between river inflow and lake water is indistinct and suggests considerable mixing. Lake outflow to the Riviere des Rochers appears to be drawing from lake water and Athabasca River water. Some flow is passing from Lake Athabasca into Chenal des Quatre Fourches.

Athabasca River flows and sediment concentrations had been relatively steady since late June, as had lake levels. Winds were relatively light and from the south. Conditions seen may be typical of later summer with steady flow conditions and relatively light winds, but it is not obvious why the water boundary north of the delta shoreline is less distinct than in most other pictures.

1 August 1977 - Band 5 Image

Lake Athabasca shows patchy turbidity and is mostly clear north of Bustard Island, except along the east shore. Lake Claire is generally light-toned, but Mamawi Lake is darker and shows patterns that may indicate bottom features. The Peace River is much lighter than Lake Athabasca outflow, which resembles Athabasca River inflow. There is a banded boundary between inflow and lake water about 3 to 5 km north of the delta shoreline, and the more westerly inflow tongues curve strongly towards the lake outlet.

21 October 1977 - Color Infrared Aerial Photography

This covers the Lake Athabasca outlet area and the greater part of the Athabasca Delta, but not much of the lake. Athabasca River channels appear light blue in the southern (upstream) part of the delta but notably darker near the channel mouths, suggesting loss of sediment towards the mouths. A 'banded' boundary between inflow and lake water appears to be only about 2 km off the delta shoreline. Dark (river) water is passing through the lake outlet into Riviere des Rochers and is mixing over a length of about 1.5 km: dark blue lake water is on the right, light blue (probably mixed) water is in the middle, annd blue-grey (probably river) water is on the left.

This is the first picture to depict autumn conditions, with relatively low inflows but fairly high lake level and outflow. The relatively low river inflow appears to have caused retraction of the usual water boundary north of the delta shore, and the outflow appears to be drawn mainly from lake water. Relatively strong winds the previous day may account in part for the complex water boundary conditions off the delta.

13 September 1978 - C1 Color Composite Image

This picture indicates very different autumn conditions from 21 October 1977. As on 26 August 1973, rotational patterns are seen in Lake Athabasca north of Burntwood Island. Athabasca River inflow is very light blue-grey in color; weed growth is easily seen as red patches off the delta shoreline, and there is a clear-cut bank of dark water, of varying width, between delta inflow and light-blue lake water.

Flows and sediment in the Athabasca River had risen rapidly during the previous three days, but Lake Athabasca levels remained relatively steady throughout September. It is possible that the sudden inflow of a slug of turbid water pushed out a pre-existing water boundary which resembled that of October 1977 or August 1977. Density difference may account in part for the sharp boundary and the apparently preferential withdrawal of river water at the outlet. Relatively strong winds may account for the light-blue turbidity in mid-lake.

Comparing this picture with that for 26 August 1973, it is evident that inflows are now curving strongly to the left, whereas in the 1973 picture they appear, if anything, to be curving slightly to the right. The difference probably reflects the effect of wind, which was from the northwest to southwest in the 1973 pictures but from the south to southeast in the 1978 one (Table 9).

4.4 DISCUSSION OF INTERPRETATIONS

The pictures reviewed in Section 4.3 yield useful information on some aspects of water and sediment circulation, but also raise questions that probably cannot be answered without field investigations coincident with satellite passes and/or photographic flights. Table 10 summarizes some of the more significant indications of the pictures and some of the questions they raise. An attempt is made below to synthesize these findings.

Table 10. Summary of indications and questions from satellite imagery and color aerial photography.

Date	Type of picture	Significant hydraulic conditions	Significant wind conditions	Boundary between river inflow and lake water	Lake Athabasca	Lake outflow	Lakes Claire and Mamawi	Questions arising
3 July 1973	Band 5	Athabasca River flood peak 1 July	Blowing along lake towards outlet	Indistinct except near lake outlet	Fairly uniform light tone S of Bustard Is.	No clear pattern	Fairly uniform light blue	Source of high turbidity in lakes?
26 Aug. 1973	Cl Composite	Lake outflow considerably exceeds river inflow; low sediment in inflow	Blowing across lake from W	Sharp, 5 to 8 km offshore	Fairly uniform light blue; gyres N of Burnwood Is.	Mainly lake water	Light blue	Do color differences indicate higher turbidity in river or lake water?
22 May 1974	Cl Composite	High inflows and flooded delta areas; some ice remnants	Blowing from S and E	Indistinct, possibly up to 13 km offshore opposite Big Point inflow	Variable dark blue-grey color	Mainly river water (probably)	Highly patterned, dark blue to light grey-blue; turbidity mainly on N side	Why are inflow and lake water apparently well-mixed? Do Lake Claire patterns reflect wind action?
2 Aug. 1974	Band 5	Flood peaks in Peace and Athabasca Rivers in July; flooded delta areas; outflow much exceeds inflow	Mainly calm	Fuzzy, 4 to 6 km offshore	Variable, mainly light tones	Mainly lake water	Mainly very light tone	Source of turbidity in Lake Athabasca? Was high turbidity of L. Claire caused by inflow from Peace R?
22 June 1975	Band 5	Steady moderate inflow, low sediment	Blowing across lake from E	Fuzzy, 4 to 7 km offshore	Dark except along W shore	Mainly river water	Uniform fairly light tone	Would color composite show stronger contrasts in Lake Athabasca? Is turbidity on W side of lake wind-induced? Source of turbidity in Lakes Claire and Mamawi?
1/2 July 1975	Cl Composite Color Infrared Aerial	Inflow high and rising rapidly, with high sediment, exceeds outflow	Blowing along lake away from outlet	Banded, moving offshore opposite Big Point inflow, up to 12 km offshore	Streaky, deep blue to light blue-grey	Both river and lake water incl. Lake Mamawi	Patchy: mid-blue to light grey-blue	Why is there a band of dark blue water between inflow and lighter lake water?
9 Aug. 1976	Cl Composite	Inflow steady and fairly low, moderate sediment	Blowing along lake away from outlet	Very fuzzy except at E end; 4 to 8 km offshore	Dark to mid-blue; lighter on W side	Both river and lake water	Fairly uniform mid-blue	Why is inflow so dark when river data indicate moderate sediment concentration? Why is boundary so fuzzy?
1 Aug. 1977	Band 5	Inflow similar to 9 Aug. 1976 but outflow much greater	Blowing along lake towards outlet	Banded, 3 to 5 km offshore	Dark to north; light patchy towards delta	Both river and lake water	Patterned, dark to light tones	Why is Peace R. so much lighter in tone than Athabasca R., despite similar sediment concentrations?
21 Oct. 1977	Color IR Aerial	Low inflow, fairly high outflow	Variable but strong	Banded, 2 km offshore	Highly patterned, dark to light blue (seen near outlet only)	Banded: river water + 2 streams of lake water (probably)	Not seen	--
13 Sept. 1978	Cl Composite	High inflow following rapid rise, fairly high sediment; exceeds outflow	Blowing across lake from SE	Sharp and banded 4 to 7 km offshore, strongly curved to lake outlet	Highly patterned with streaks and gyres	Mainly river water	Patterned, dark to mid-blue	Does darker water around E shore of lakes reflect wind from E?

4.4.1 Location and Nature of Boundary Between Inflow and Lake Water

Nearly all pictures show some form of boundary between Athabasca River inflow and the main water body of Lake Athabasca, and the general shape of the boundary is similar in most cases. The distance of the boundary from the delta shoreline appears to depend mainly on lake inflow, extending farthest with higher inflows, as might be expected. However, comparison of pictures from 9 August 1976 and 1 August 1977, when inflows were similar, suggests that greater outflows, resulting in more withdrawal of lake water, may produce retraction of the boundary towards shore.

The sharpness and width of the boundary zone is quite variable. Varying degrees of sharpness presumably reflect the degree of mixing between river and lake water, which is likely to depend on density differences due to temperature and turbidity and on general stability conditions in the lake. There is no obvious association between boundary sharpness and other factors listed in Tables 9 or 10. The reason for 'banded' boundaries is not evident in several cases.

It would appear from these pictures that inflow from the Athabasca River seldom extends farther than about 10 km from the river channel mouths at the point of greatest influence, that is, the mouth of Big Point Channel. More commonly, the area of river water is from 5 to 8 km wide at its widest point. River water appears to advance farthest into the lake (up to 13 km or so) when lake levels are high, the whole delta area is flooded, and outflow is restricted by high Peace River levels.

The location of the boundary appears to correspond closely to the outer limit of significant sand content in bottom sediments, as indicated by Figure 11 and Section 3.5.

4.4.2 Source of Main Lake Outflows Via Riviere des Rochers

It is fairly evident that the proportions of 'river' and 'lake' water entering the outlet depend in part on the relation of

Athabasca River inflow to Riviere des Rochers outflow. When outflow considerably exceeds inflow (26 August 1973; 2 August 1974; 1 August 1977; 21 October 1977), lake water is dominant or prominent in the outflow. When inflow considerably exceeds outflow (22 May 1974), river water appears to be dominant. Undoubtedly, however, other factors are likely to be involved as well: lake level, wind, density differences, etc.

4.4.3 Turbidity Patterns in Main Body of Lake Athabasca

It appears likely that these are determined largely by wind and wave conditions, although in many cases the association with immediately preceding wind conditions is not evident.

4.4.4 Turbidity in Lakes Claire and Mamawi

These shallow lakes sometimes appear uniformly turbid and sometimes appear highly patterned. Wind and wave conditions are probably the most important factors, but backflow from Lake Athabasca and flooding from the Peace River are sometimes involved.

4.4.5 Interpretive Difficulties

The main difficulty occurs over color differences in Cl composite images, for example that of 26 August 1973 when Lake Athabasca is a uniform light blue and river inflow is a much darker grey-blue. It is not clear how these differences relate to sediment or other characteristics of the water, and to what extent they reveal bottom conditions rather than water turbidity. Other difficulties arise over tonal differences in Band 5 images, which do not always seem to correlate with reported sediment concentrations; for example on 1 August 1977, when the Peace River appeared much lighter than the Athabasca River although concentrations appeared to be similar.

5. ANALYSIS OF PREVIOUS WATER QUALITY DATA

5.1 BACKGROUND

The two largest inflows to Lake Athabasca are the Athabasca River, which drains approximately 154 000 km^2 of the Interior Plains and east slopes of the Rocky Mountains, and the Fond du Lac River, which drains approximately 82 000 km^2 of the Canadian Shield east of Lake Athabasca. The water of the Athabasca River can be described as highly variable in both filterable and non-filterable residues, moderately hard, and moderately to highly turbid. In contrast, the waters of the Fond du Lac River Basin are characteristically soft and clear due to consistently low amounts of filterable and non-filterable residues (Seidner 1979). Because of these differences, it should be possible to use standard water quality parameters to identify the sources of water in the lake.

Seidner (1979) describes a field survey which shows how a water quality parameter, in this case specific conductance, can be used as a tracer to identify the two water types. Figure 19 shows the spatial variation of specific conductance along three transects within the lake. As can be seen, a distinct boundary exists north of the delta where the Athabasca River mixes with Lake Athabasca water. The specific conductance drops sharply from about 270 S /cm for Athabasca River water to about 95 S/cm for Lake Athabasca water. The sharpness of the boundary was interpreted as indicating very little mixing between the two water types. Comparison of Figure 19 with contemporaneous aerial photography (Figure 18f) suggests that the water quality boundary corresponds closely in this case with a color boundary between darker (river) water to the south and lighter (lake) water to the north.

Water quality parameters can also be used to determine the extent of mixing of two waters. When waters mix, resulting values of quality parameters are intermediate between their original values. Lipsett and Beltaos (1979) used water quality parameters to evaluate the mixing characteristics downstream of the confluence of two streams, and similar techniques can be used to assess the mixing of the two waters in Lake Athabasca and further downstream in the

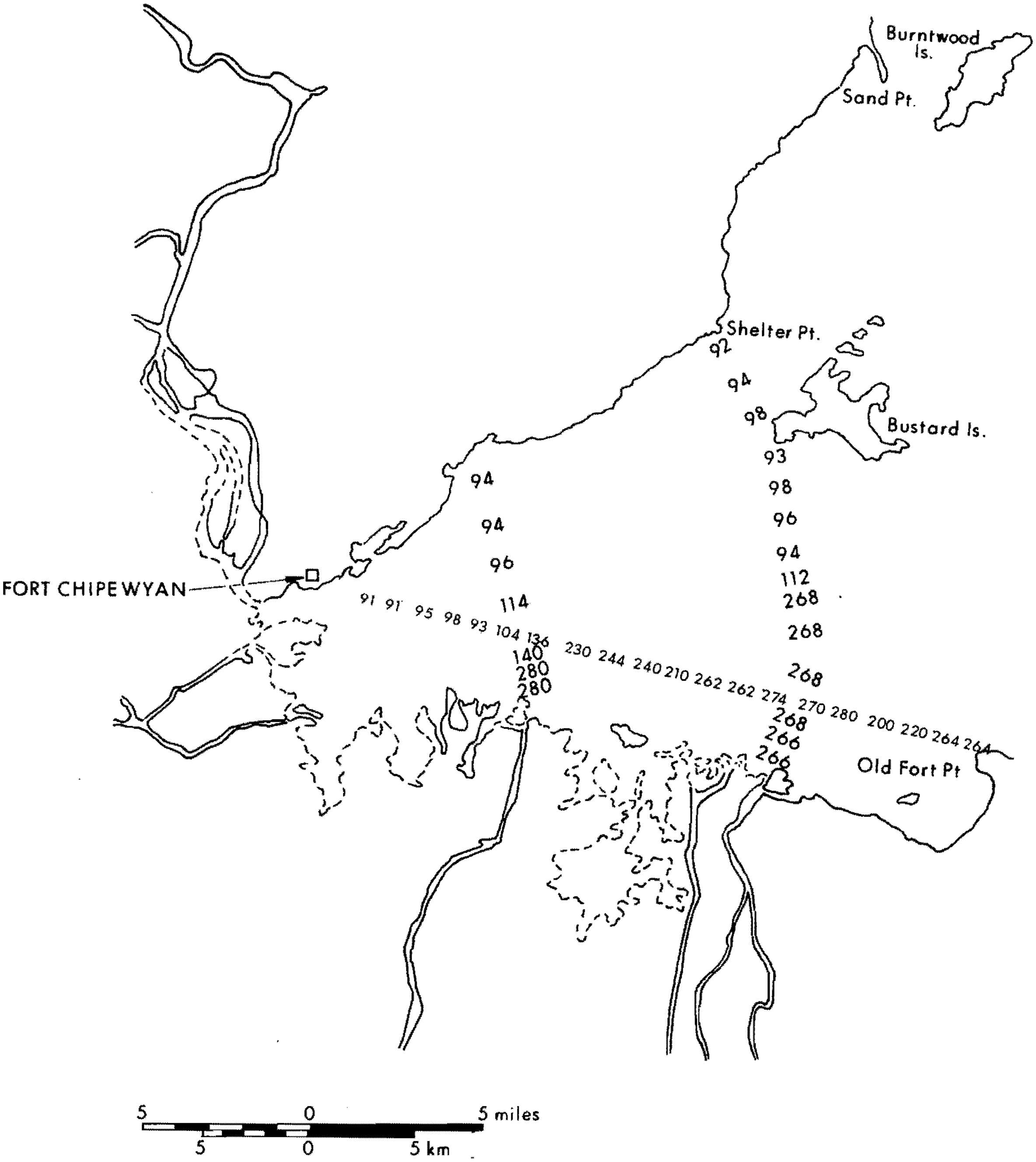


Figure 19. Variation of specific conductance (μS/cm) at southwest end of Lake Athabasca, 22 October 1977. From Seidner, 1979.

Riviere des Rochers. Although this would normally require extensive field surveys before firm conclusions on the mixing characteristics could be drawn, some comments can be made on the basis of limited field data. For example, if values of certain water quality parameters are known at certain times in the Athabasca River, in Lake Athabasca far removed from the mixing region, and in the Riviere des Rochers, then it is possible to estimate the relative volumes of water from each of the two sources which are flowing out of Lake Athabasca into the Riviere des Rochers.

If the concentration of a water quality parameter is C_A in the Athabasca River, C_L in the Lake Athabasca, and C_R in the Riviere des Rochers, then it can be shown that the proportions of outflow originating from each water source are given by:

$$\frac{Q_A}{Q_R} = \frac{C_R - C_L}{C_A - C_L}$$

or by

$$\frac{Q_L}{Q_R} = \frac{C_R - C_A}{C_L - C_A}$$

where Q_R is the total rate of outflow, and Q_A and Q_L are partial rates due to Athabasca River and Lake Athabasca water respectively. It is assumed that the waters are fully mixed in the Riviere des Rochers and that C_R represents the final mixed concentration.

For definitive background on water quality parameters, reference may be made to McNeely et al (1979).

5.2 DATA AND ANALYSIS

An extensive water sampling program has been carried out for AOSERP by the Water Quality Control Branch, Pollution Control Division of Alberta Environment, and a summary of this data has been presented by Seidner (1979).

Table 11 shows the minimum, median, and maximum values of six water quality parameters obtained at six sampling stations in the study area in 1977. These are the parameters which show the greatest differences from west to east and are therefore the best

Table 11. Ranges of water quality data during 1977 for selected points in study area.

Parameter[a]	Lake Claire east of north end of Birch River			Lake Claire at at 28th baseline			Prairie River			Mamawi Lake Channel			Athabasca River at Big Point Channel			Lake Athabasca at Sand Point		
	min.	med.	max.	min.	med.	max.	min.	med.	max.	min.	med.	max.	min.	med.	max.	min.	med.	max.
Calcium	37.5	40.8	44.0	32.5	46.0	55.0	32.5	36.0	41.0	26.0	29.5	40.0	25.5	28.0	33.0	8.8	9.5	9.5
Sodium	33.0	36.0	42.0	37.5	52.5	60.0	7.5	26.5	38.5	7.5	8.4	38.0	7.5	8.1	13.0	2.8	3.2	3.5
Potassium	3.0	3.4	3.3	2.5	3.4	3.6	1.8	2.6	3.3	1.1	1.4	3.2	1.1	1.2	1.3	1.0	1.0	1.1
Chloride	38.0	46.7	54.5	44.0	71.5	76.0	5.3	31.8	46.0	5.3	6.2	43.0	5.4	7.2	11.0	3.4	3.5	3.5
Sulphate	42.2	58.0	70.5	47.5	86.5	90.0	19.7	41.0	51.0	9.9	11.6	57.5	10.0	13.9	14.0	2.4	4.4	6.9
Conductance	420	445	480	430	548	610	255	380	453	210	237	438	206	231	237	75	79	85

[a] Ion concentrations in mg/L
Specific conductance in μS/cm

ones for distinguishing the origins of a water sample. It can be seen that ion concentrations and conductances are very much greater in Lake Claire than in the Athabasca River. Sources of various salts, known to exist in the drainage area of the Birch River and also north and west of Lake Claire, are presumably the reason for greater ion concentrations.

Values of water quality parameters in the connecting channels between Lake Athabasca and Lake Claire are good indicators of the flow directions in these channels. For example, a relatively high concentration of sodium on a given day in Mamawi Lake Channel between Mamawi Lake and Quatre Fourches indicates that water from Lake Claire is flowing into the Chenal des Quatre Fourches. Conversely is a relatively low sodium concentration indicates that Lake Athabasca water is flowing into Mamawi Lake.

Data from the sampling program have been used to evaluate Lake Athabasca outflow proportions for seven sampling dates from 1977 through 1979. The sampling sites pertinent for this analysis are Athabasca River at Big Point Channel, Lake Athabasca at Sand Point (near Burntwood Island - see Figure 1), and Riviere des Rochers 150 m upstream of the head of Revillon Coupe. It is assumed that a fully mixed condition existed at the Riviere des Rochers site.

Table 12 shows calculated values of Q_A/Q_R, the proportion of Athabasca River water in the Riviere des Rochers, based on a series of water quality parameters for each of seven sampling dates. An average ratio is also shown for each date. As can be seen, the proportions computed using different parameters are fairly consistent for each sampling date. A strong seasonal variation is evident: it is clear that most of the water flowing out of the lake in the summer months originates from the Athabasca River. The ratio declines through the summer and early fall, and drops dramatically in late fall and winter. The average value of 0.08 calculated for January 1979 indicates that virtually no Athabasca River water was leaving Lake Athabasca. Further information on this topic is discussed in Part 6.

Table 12. Proportions of Athabasca River water in Lake Athabasca outflow as calculated from water quality parameters.

Date	Proportion Q_A/Q_R as determined from property or ions listed[a]								Average Proportion
	Specific Conductance	Ca	Mg	Na	Cl	SO_4	HCO_3	$CaCO_3$	
July 5, 1977	.79	.89	.84	.89	.45	.46	.88	.88	.76
August 16, 1977	.65	.63	.63	.58	.63	.54	.64	.66	.63
September 27, 1977	.53	.50	.50	.47	.62	.29	.51	.51	.49
October 25, 1977	.19	.18	.18	.14	.13	.30	.19	.20	.19
June 27, 1978	.86	.94	.94	.84	1.25	.86	.82	.89	.92
August 7, 1978	.89	.84	.84	.87	1.08	.90	.84	.86	.89
January 9, 1979	.07	0	0	.17	.16	.19	0	0	.08

[a] Q_R = total flow in Riviere des Rochers

Q_A = partial Riviere des Rochers flow originating from Athabasca River.

6. FIELD INVESTIGATIONS 1979-80

Three separate field programs were carried out in the course of the study. The first was a one-day reconnaissance by floatplane on 7 September 1979. The second was a one-day repeat survey by helicopter on 25 March 1980. The third was a six-day series of field investigations conducted between 11 and 16 June 1980.

Figure 20 shows measurement locations in and near Lake Athabasca for all three field studies, which are described separately in Sections 6.1, 6.2 and 6.3. Location numbers for the September 1979, March 1980 and June 1980 programs are prefixed S, M and J respectively. Measurement locations beyond the limits of Figure 20 are described in the appropriate data tables.

Table 13 summarizes key hydrologic data for the periods of the three field investigations.

6.1 RECONNAISSANCE IN SEPTEMBER 1979

6.1.1 Objectives

A field reconnaissance by floatplane was undertaken on 7 September 1979 to measure a number of water quality parameters at selected locations in the study area. It was planned to acquire color infrared aerial photography from a high altitude at the same time. The objectives of the study were:

(i) to determine the most suitable water quality parameters as indicators of water and sediment movement through the Delta; and

(ii) to obtain 'ground truth' information in conjunction with aerial photography, and thereby improve the interpretation of previous LANDSAT imagery and aerial photography.

6.1.2 Procedure and Results

It had been planned to conduct the reconnaissance in clear weather that would permit vertical aerial photography to be taken simultaneously. Persisting low cloud over a period, however, prevented acquisition of the aerial photography. Measurements of water quality parameters were made as intended, and a limited number of oblique color and infrared photographs were taken from low

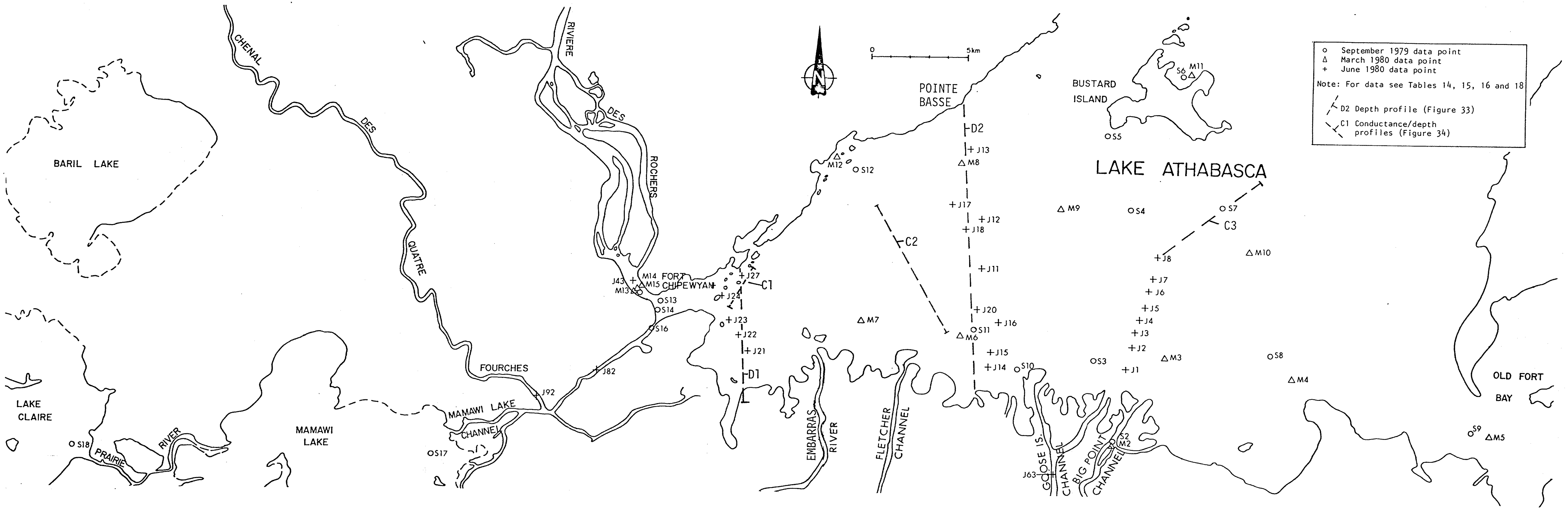


Figure 20. Field measurement locations in September 1979, March 1980, and June 1980.

Table 13. Key hydrologic data for periods of 1979-80 field investigations.

Date	Athabasca River discharge m^3/s	Outflow from Lake Athabasca m^3/s	Water Level in Lake Athabasca m
7 Sept. 1979	810[1]	2250	209.5
25 March 1980	200[1]	800[3]	208.2 (ice conditions)
11 June 1980	3820[2]	430	
16 June 1980	1830	1870	
Average 11-16 June	2510	1420	208.75

[1] Data for Embarras gauging station

[2] Based on data for Fort McMurray, allowing 1 day time lag. See Figure 26 for hydrograph of daily flows.

[3] Alberta Environment estimate for Riviere des Rochers = 750 m^3/s.

altitude. Figure 21 shows selected photographs. No useable satellite imagery is available within an appropriate time before or after the reconnaissance date.

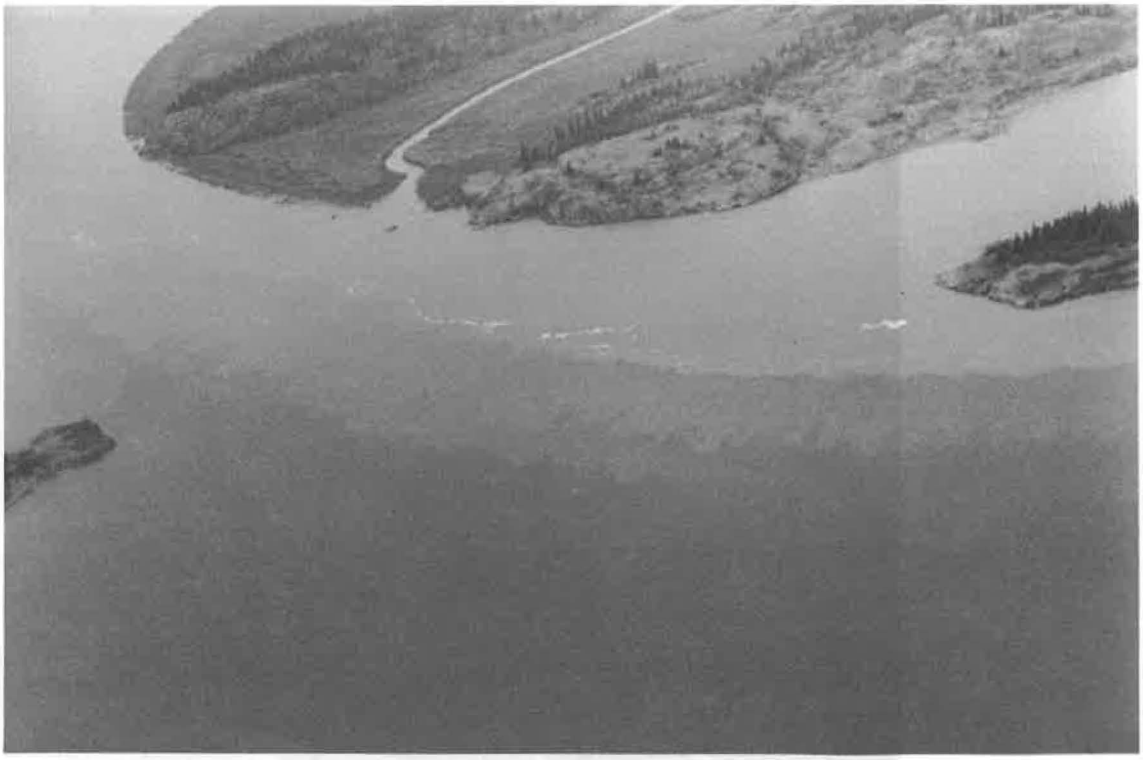
The floatplane was used to land at twenty points in the study area, as shown in Figure 20. Of the twenty sites, one was in the Athabasca River below the Embarras River, one in the mouth of Big Point Channel, three in Lake Claire, one in the Riviere des Rochers just below the lake outlet, and the remaining thirteen in Lake Athabasca. Water depth, water temperature, dissolved oxygen, pH and specific conductance were read at each site using portable sounding and water quality metering equipment. Water samples were collected at each site and all were subsequently analyzed for turbidity by Chemical and Geological Laboratories Ltd. Specific conductance, suspended solids, calcium, magnesium and bicarbonates were also determined for six of the samples. Table 14 lists the field and laboratory results.

By comparing Table 13 and Table 9, it can be seen that inflow and outflow conditions were quite similar to those of 21 October 1977, for which color infrared aerial photography is available over an area near the lake outlet (Figure 18f). This earlier photography shows a band of dark blue water along the north shore near the lake outlet. Such a band was not seen, however, on 7 September 1979 (Figure 21a).

6.1.3 Discussion of Water Quality Parameters

The various parameters recorded in Table 14 are discussed below.

1. Temperature. Maximum water temperature was 14.6^{o}C at the mouth of Big Point Channel and minimum was 12.0^{o}C in Old Fort Bay. Temperature does not appear to be a useful indicator of water source.
2. Dissolved oxygen. The range of values is small and it therefore does not appear to be a useful indicator of water source.
3. pH. Water in the Athabasca River, in Lake Athabasca near the Athabasca Delta, at the outlet to Riviere des Rochers,



(a) Entrance to Riviere des Rochers (ordinary color)

(b) Quatre Fourches looking west (color infrared)

Figure 21. a and b. Photographs from field reconnaissance of 7 September 1979.

(c) Birch River Delta looking west (ordinary color)

(d) Birch River Delta looking west (color infrared)

Figure 21. c and d. Photographs from field reconnaissance of 7 Septemb
1979.

Table 14. Water quality data from field reconnaissance of 7 September 1979.

	Field readings					Laboratory analyses of samples from a depth of 1 m or less						Location description
									Dissolved Solids			
Location No.[a]	Water Depth m	Water Temperature[b] °C	Dissolved Oxygen ppm	Hydrogen Ions pH	Specific Conductance µS/cm[c]	Specific Conductance µS/cm at 25°C	Turbidity NTU[d]	Suspended Solids mg/L	Calcium mg/L	Magnesium mg/L	Bicarbonate mg/L	
S 1	3.7	14.2	9.4	8.2	270		31	36	30.6	7.6	120	Athabasca River
S 2	0.9	14.6	9.0	8.1	260		14					Mouth of Big Point Channel
S 3	3.4	12.6	9.5	8.1	150		61					Lake Athabasca, 3 km N of Goose Is. channel
S 4	3.7	12.5	9.7	7.9	110		38					Lake Athabasca, 10 km N of Goose Is. channel
S 5	3.1	13.0	9.5	7.8	110		24					Off SW tip of Bustard Island
S 6	4.3	12.8	9.4	7.8	110	108	62	79	11.7	3.1	50	Bay on N side of Bustard Island
S 7	4.3	12.9	9.6	7.9	110		41					4 km SE of Bustard Island
S 8	3.1	12.6	9.9	8.1	140		48					2 km NW of Old Fort Point
S 9	1.5	12.0	9.7	7.9	150		3					Old Fort Bay (clear water)
S10	1.1	13.8	9.2	8.3	250		10					2 km N of Goose Island (fairly clear water)
S11	3.1	12.5	9.5	8.2	200		52					4 km NE of Fletcher Channel
S12	2.1	12.8	9.5	7.9	110		57					Near shore, 10 km NE of Fort Chipewyan
S13	16.8	12.6	9.5	8.2	210		55					Entrance to R. des Rochers (light to silty water)
S14	1.5	12.8	9.7	8.3	270	261	21	32	31.5	7.7	120	Entrance to R. des Rochers (dark water)
S15	10.2	12.6	9.8	8.1	150	144	60	92	17.4	4.2	66	R. des Rochers, opposite Dog Head Point
S16	3.7	13.0	9.6	8.4	270		12					NE arm of Quatre Fourches at Lake Athabasca
S17	1.2	12.2	9.7	8.4	400		36					East end of Mamawi Lake
S18	0.8	12.6	9.7	8.4	400		35					East end of Lake Claire
S19	0.9	13.4	8.8	7.7	400	393	31	49	32.2	9.2	100	L. Claire off Birch R. delta (dark brown water)
S20	1.2	13.0	10.0	8.3	530	534	51	63	46.8	11.2	130	L. Claire off Birch R. delta (light silty water)

[a] See Figure 20 for map locations

[b] Temperature profiles were taken at nearly all locations, but no gradients or changes were found

[c] microSiemens (micromhos) per centimetre

[d] Nephelometric Turbidity Units

in Lake Mamawi and in most of Lake Claire had pH values in the range of 8.1 to 8.4. Lower values in the range of 7.0 to 7.7 were found in Old Fort Bay, in Lake Claire near the Birch River delta and in Lake Athabasca near Bustard Island. These areas of lower pH probably reflect runoff from the Canadian Shield that surrounds most of Lake Athabasca, or, in the case of Birch River, from muskeg terrain. The usefulness of this parameter as a source indicator appears to be moderate.

4. Specific conductance. The large range of values makes this parameter very useful for distinguishing water sources. Athabasca River water registered about 260 S/cm, while in Lake Athabasca around Bustard Island and along the north shore the value was about 110. In the Riviere des Rochers the value was about 150, while in Lakes Claire and Mamawi the range was from 400 to 530.
5. Turbidity. Measured values range from 3 to 62 Nephelometric Turbidity Units (NTU). The lowest value was for the clear water of Old Fort Bay, while the highest value was measured on the north side of Bustard Island. In the Athabasca River upstream of the Delta and in Big Point Channel, values were 31 and 14 respectively. At the entrance to the Riviere des Rochers the light, apparently silty water registered 55 NTU and the darker water nearby registered 21. Figure 21a shows the visual appearance of these distinct waters at the entrance to the Riviere des Rochers. It appears that on the survey date the main body of Lake Athabasca was more turbid than Athabasca River inflow. Similar conditions seem to be indicated by analyzed pictures of 26 August 1973 and 21 October 1977 - see Section 4.3 and Figures 18a and f. It is not clear whether the higher turbidity of Lake Athabasca is due to wind-wave effects or to persistence of earlier inflows.
6. Suspended solids. A plot of suspended solids concentration versus turbidity (Figure 22) shows a good correlation for the available data. It therefore appears that suspended sediment concentration could be estimated reasonably from

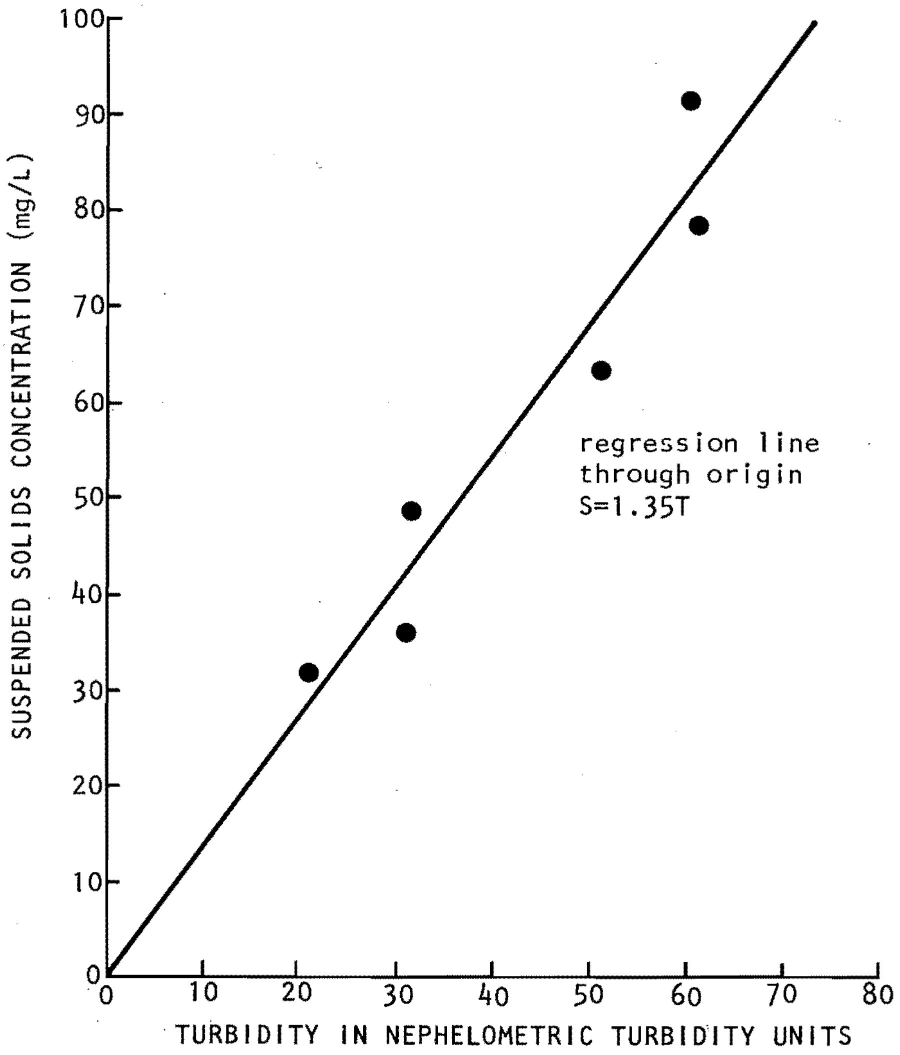


Figure 22. Suspended solids concentration vs. turbidity for samples from field reconnaissance of 7 September 1979.

turbidity measurements, at least over the range shown. Turbidity can be measured in the field, although this was not done in the reconnaissance.

7. Calcium, Magnesium and Bicarbonate. Concentrations of these ions correlate closely with specific conductance for samples from the Athabasca River, Lake Athabasca and Riviere des Rochers. For Lake Claire, specific conductances are much higher in relation to the ions reported in Table 14. The 1977 data in Table 11 show that the high conductance in Lake Claire results largely from sodium chloride and sulphates.

In summary, specific conductance appears to be the most convenient parameter for tracing water sources and movements.

6.1.4 Comparison with October 1977 Conditions

Specific conductance data reported by Seidner (1979) for 25 October 1977 were shown in Figure 19 and discussed in Section 5.1.1, and a sample of associated aerial photography of 21 October 1977 was shown in Figure 18 f and discussed in Section 4.3. Both conductance data and aerial observations for the September 1979 reconnaissance suggest that circulation and mixing conditions were quite similar to those of October 1977. Water from the Athabasca River was flowing westward from the various delta distributaries to the Riviere des Rochers, and mixing with water from the main body of Lake Athabasca at the head of the Riviere des Rochers. In the Quatre Fourches secondary outlet system, water was flowing westward from Lake Athabasca and eastwards from Mamawi Lake to join at Quatre Fourches (see Figure 21b), then flowing north to the Peace River.

Figure 23 shows specific conductance data from 7 September 1979 superimposed on Seidner's data from 22 October 1977. Also shown are the approximate limits of the light color band seen in airphotos of 21 October 1977. It appears that this band corresponds roughly to the zone of mixing of river and lake water.

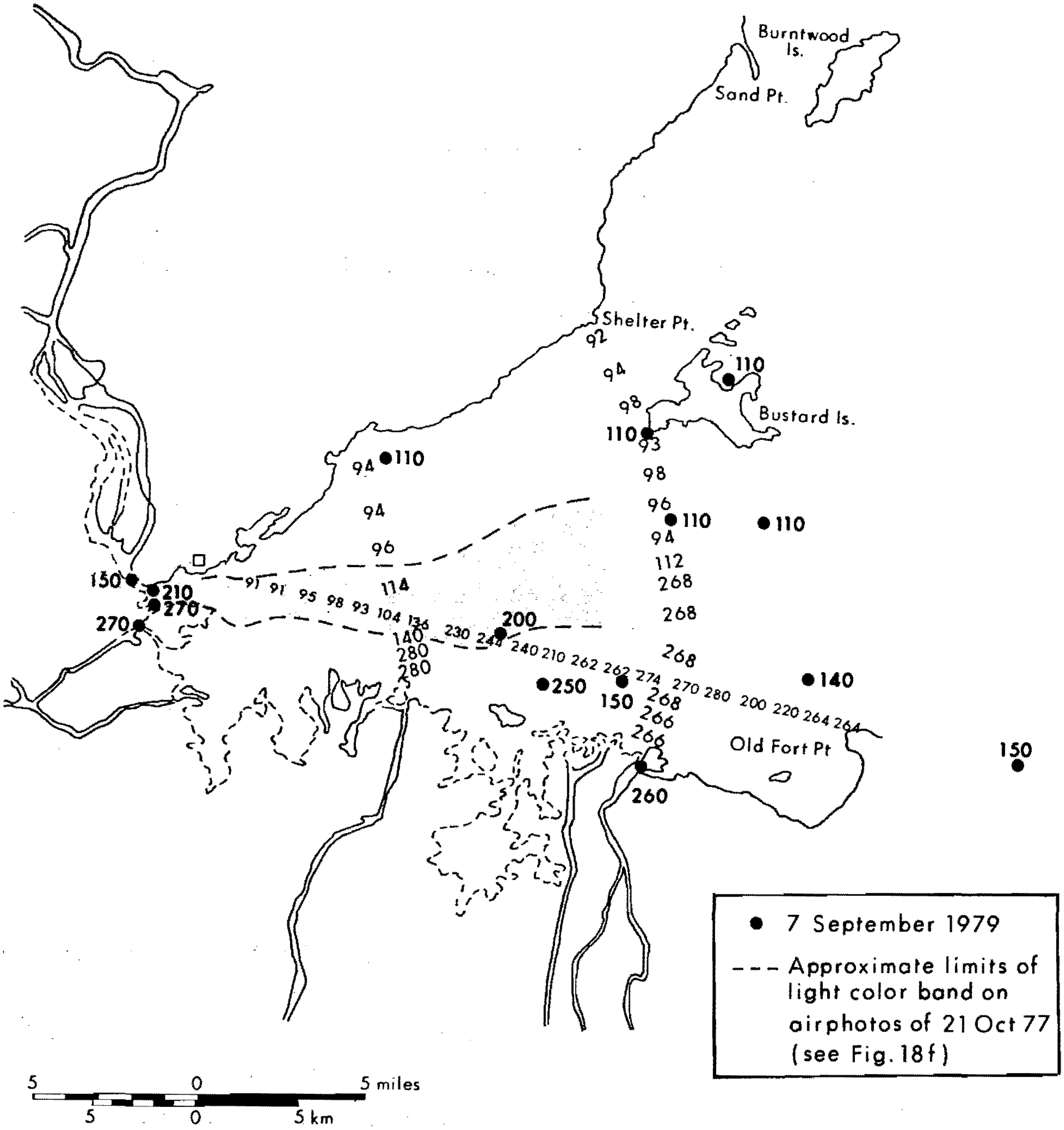


Figure 23. Specific conductance data from 7 September 1979 superimposed on Seidner's data for 25 October 1977 (from Figure 19).

6.2 SURVEY IN MARCH 1980

6.2.1 Objectives

A winter survey was undertaken on 25 March 1980, essentially as a repeat of the September 1979 reconnaissance under winter conditions. In addition to water quality measurements, attention was given to determining ice thicknesses, water circulation, and thermal regime under the ice.

6.2.2 Procedure and Results

A helicopter was used to land at fifteen points in the study area as shown in Figure 20. Of these sites, one was in the Athabasca River below the Embarras River, one in the mouth of Big Point Channel, three in the Riviere des Rochers just below the lake outlet and the remaining ten in Lake Athabasca. Water depth, ice thickness, water temperature, specific conductance, dissolved oxygen and pH were read using portable sounding and water quality metering equipment. Water samples were taken at each site and subsequently analyzed for chloride and total dissolved solids concentration by Chemical and Geological Laboratories Ltd. Table 15 lists the field and laboratory results.

6.2.3 Discussion of Results

The following comments are in order for several parameters listed in Table 15.

1. Water temperature. Negative values of as low as -0.3^{0} C were measured at most locations beneath the ice. It is possible that these values are due to ice coating on thermistor probes and that the correct value should be 0^{0} C.
2. Dissolved oxygen. Values are mostly between 10 and 15 mg/L. The saturation level at sea-level at 0^{0} C is approximately 15 mg/L. Only one value, near Old Fort Point, is less than 10 mg/L.

   Values in September 1979 (Table 14) were generally 9 to 10 mg/L, at a water temperature of about 13^{0} C; these were also close to saturation levels.

Table 15. Data from field survey of March 25, 1980.

Location No. (see Fig. 20)	Ice thickness m	Depth of water below top of ice m	Sample depth below top of ice m	Temp. °C	pH	Specific conductance µS/cm	Chloride[2] concentration mg/L	Dissolved oxygen mg/L	Velocity cm/s	Direction[1] degrees	Location Description
M1	0.60	6.02	2.0	0	7.57	413	34.0	10.95			Athabasca River near Embarrass Airport
			4.0	-0.05	7.57	414		11.25			
M2	0.70	4.25	1.0	-0.1	7.75	371	34.5	10.97			Mouth of Big Point Channel
			2.0	-0.1	7.69	371		10.83			
			3.0	-0.2	7.66	377		10.79			
			4.0	-0.2	7.64	378		10.73			
M3	1.10	1.15	1.15	-0.3	7.46	376	32.5	10.24	0		4.5 km NE from mouth of Big Point Channel
M4	1.00	2.10	1.5	+0.3	7.25	237	34.0	8.20	0		1.0 km NW Old Fort Point
M5	0.74	0.74	no water				--				Old Fort Bay
M6	0.87	1.17	1.15	-0.3	7.39	409	34.8	10.89	0		3.0 km north of Goose Island
M7	0.98	1.08	1.0	-0.3	7.41	407	34.8	10.99	0		3.0 km north of mouth of Embarrass River
M8	0.75	2.00	1.4	-0.1	7.28	93	5.8	14.13	5	61	12.0 km north of Goose Island
M9	0.90	2.40	1.4	-0.1	7.39	98	6.4	14.20	3	62	5.0 km SW of Bustard Island Island
M10	0.82	2.96	1.4	+0.6	7.18	102	5.9	11.27	4	65	9.5 km NE from mouth of Big Point Channel
M11	1.00	2.79	2.0	+0.5	7.06	101	5.9	14.92	0		Bay on north side of Bustard Island
M12	1.05	1.05	no water				--				10 km NE of Fort Chipewyan off island
M13	0.82	20.8	3.0	-0.2	7.5	110	6.1	14.45	not measured but qualitatively "fast"		Riviere des Rochers at lake outlet, 90m from left bank
			5.0	-0.2	7.48	109		14.40			
			7.0	-0.3	7.46	131		14.20			
			9.0	-0.3	7.44	143		13.56			
			11.0	-0.3	7.45	134		13.43			
			13.0	-0.3	7.38	156		13.37			
			15.0	-0.3	7.38	220		12.70			
			17.0	-0.3	7.37	230		12.46			
			19.0	-0.3	7.37	238		12.33			
			20.8	-0.3	7.37	233		12.30			
M14	0.82	17.55	3.0	-0.3	7.47	106	6.0	14.26	not measured but qualitatively "fast"		Riviere des Rochers at lake outlet
			6.0	-0.3	7.43	144		13.55			
			9.0	-0.3	7.42	160		13.49			
			12.0	-0.3	7.40	167		13.59			
			15.0	-0.3	7.39	180		12.90			
M15	0.70	5.49	3.0	-0.3	7.53	105	5.4	15.20			Riviere des Rochers at lake outlet, 230m from left bank 46 m from right bank
			5.0	-0.3	7.49	104		14.30			

---

[1] Indicates direction from which current was flowing, referred to north as zero

[2] Laboratory measurement: other parameters are field measurements.

3. pH. Values are generally around 7.5; in September 1979 they were around 8.0.
4. Specific conductance. Values are mapped in Figure 24. As in September 1979 (Figure 23) there is a strong contrast between Athabasca River water, now with a value of about 400 S/cm, and Lake Athabasca water well out in the lake, with a value of about 100 S/cm. At the lake outlet (Riviere des Rochers inlet), there was a distinct conductivity gradient from near 100 at the surface to over 200 at the bottom (Figure 25) suggesting density stratification associated with salinity differences. The average conductance at the lake outlet is approximately 160 S/cm. The vertical stratification evident in Figure 25 probably results from rotation of the horizontal specific conductance differences evident in Lake Athabasca (see Table 15).
5. Chloride. There is a close correlation between specific conductance and chloride ion concentration.
6. Currents. Lake currents were detected at only 3 points (see Figure 24), all well out in the lake. These data indicate a general flow of Lake Athabasca water towards the outlet, at a velocity of approximately 4 cm/s.
   Assuming a flow width of 10 km and a flow depth of 1.5 m, the discharge of lake water to the outlet can be estimated as about 600 m^3/s. Added to an Athabasca River inflow of about 200 m^3/s, the total outflow from the lake should be approximately 800 m^3/s. Alberta Environment data indicate that the discharge in Riviere des Rochers was approximately 750 m^3/s. Correspondence between these figures is remarkably good given the crudity of the lake data. Conductance data at the lake outlet, plotted in Figure 25, confirm that the proportions of lake and river water leaving the lake were approximately 75% and 25% respectively.

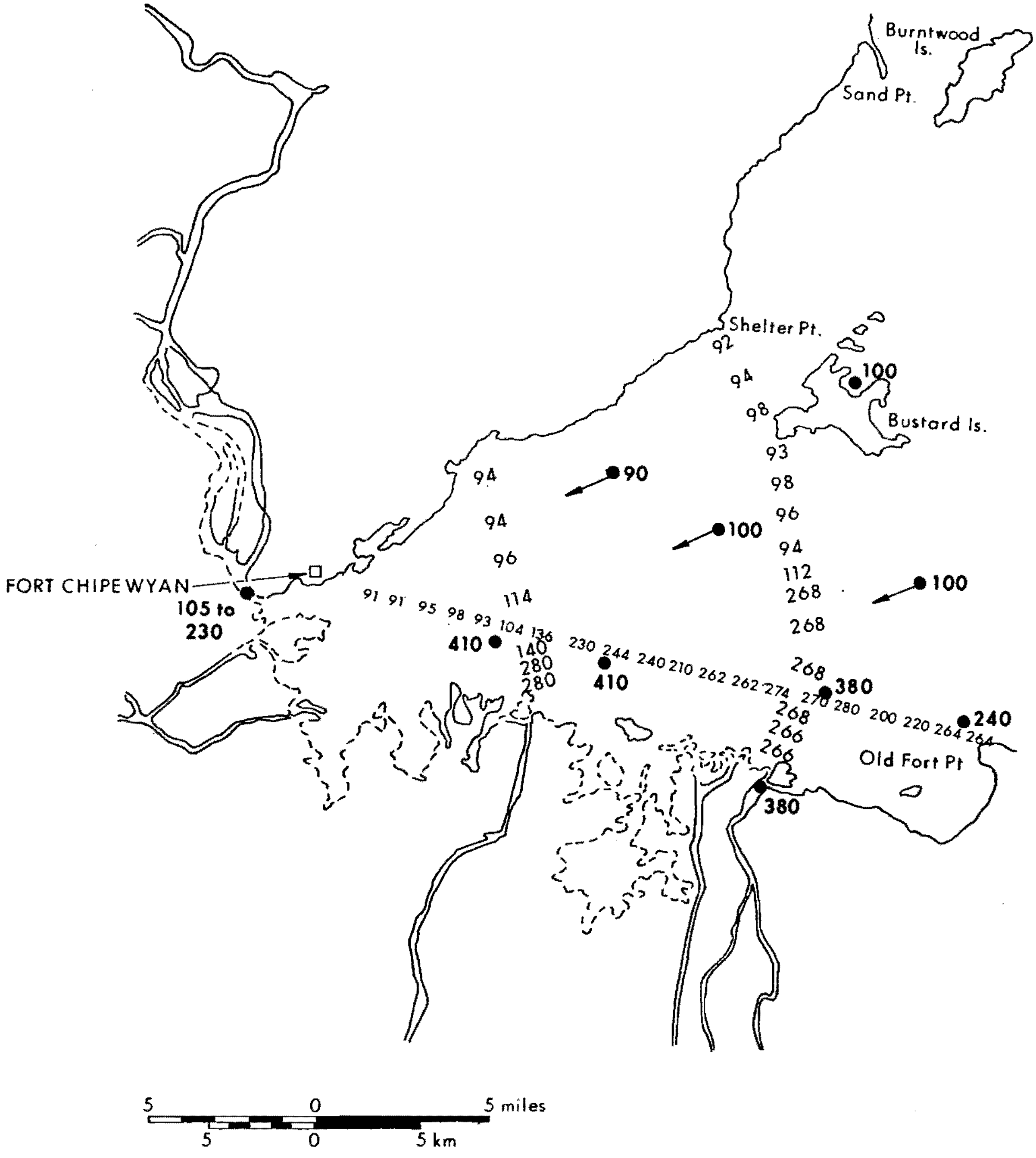
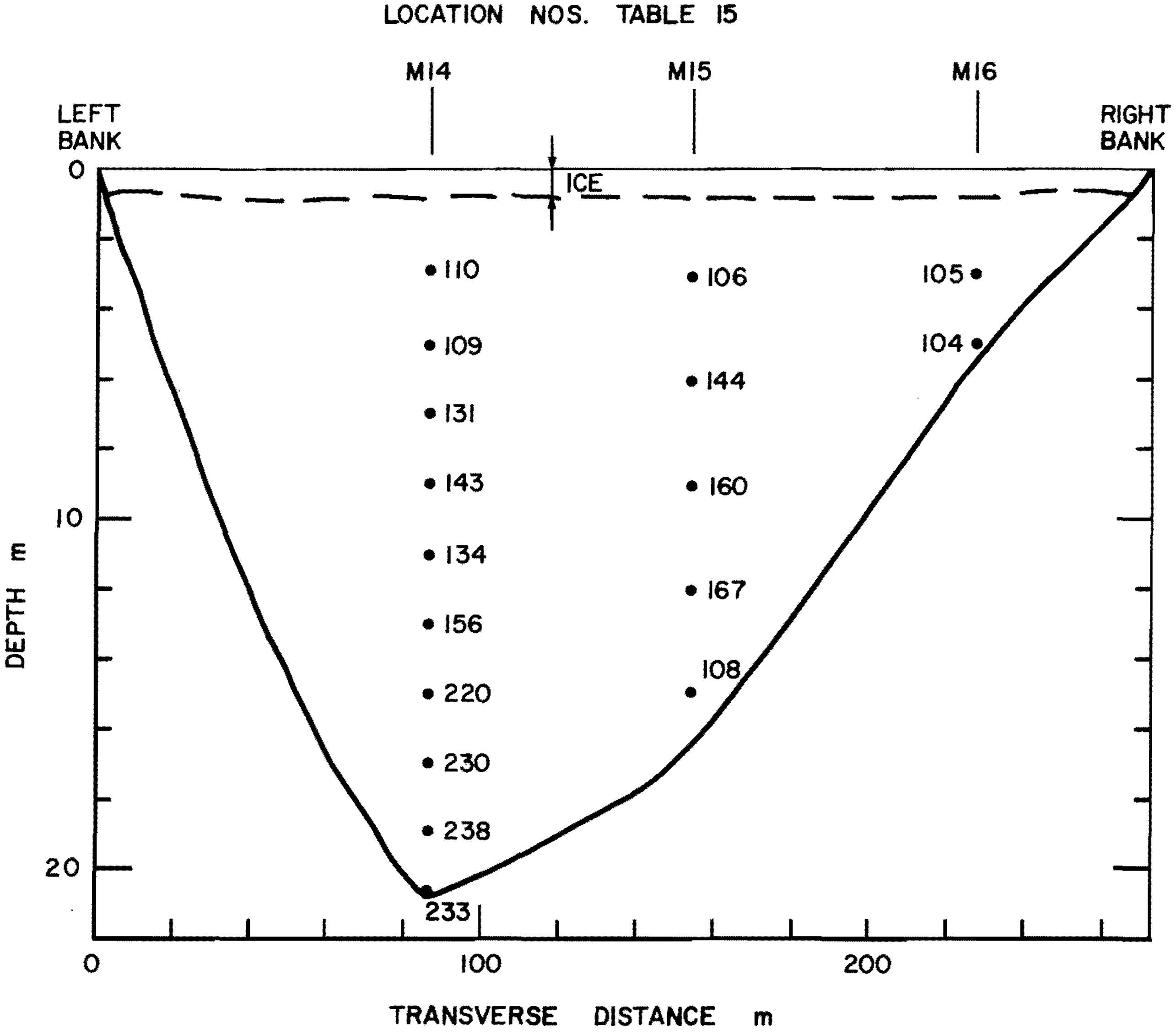


Figure 24. Under-ice conductances and current directions from 25 March 1980 superimposed on Seidner's (1980) data for 25 October 1977.



LEGEND: ● 220 SPECIFIC CONDUCTANCE µS/cm

Figure 25. Cross-section of Rivere des Rochers near outlet of Lake Athabasca, showing conductance distribution on 25 March 1980.

6.3 SURVEYS IN JUNE 1980

6.3.1 Objectives

A field program was mounted from 11 to 16 June 1980, to obtain selective information on flow, sediment and mixing conditions at various points in the delta and lake system, and to utilize these in part as 'ground truth' for interpretation of remote sensing data. At this time the Athabasca River was carrying a high flow and sediment load. The field program was integrated to some degree with a field program for the Slave River hydroelectric feasibility studies, conducted for Planning Division of Alberta Environment.

The program timing was planned to straddle overpasses by the LANDSAT 3 satellite on 12-14 June. Although weather was clear, it was discovered later that satellite sensors had not been in operation during these overpasses. Excellent imagery was however obtained from a LANDSAT 2 overpass on 22 June, when Athabasca River inflow had dropped somewhat but conditions were otherwise similar.

No special vertical aerial photography was arranged in conjunction with the ground program, partly because of difficulties experienced in attempting to schedule airphotography in September 1979. A series of photographs was however taken from a chartered aircraft at relatively low altitude on 13 June.

6.3.2 Hydrologic and Meteorologic Conditions

A hydrograph of estimated Athabasca River inflows during the period of interest, based on Water Survey of Canada preliminary data for Fort McMurray, is shown in Figure 26. By accident, the program started at the peak of the 1980 Athabasca River flood, which as it happens was of approximately 10-year return period. Water Survey of Canada suspended sediment data for the Athabasca River were not available at time of writing.

By comparing Table 13 with Table 9, it can be seen that the Athabasca River inflow in the June 1980 survey period was slightly higher than at any of the earlier dates for which remote sensing data were analyzed in Section 4.3. The most comparable of these previous conditions were those for 2 July 1975.

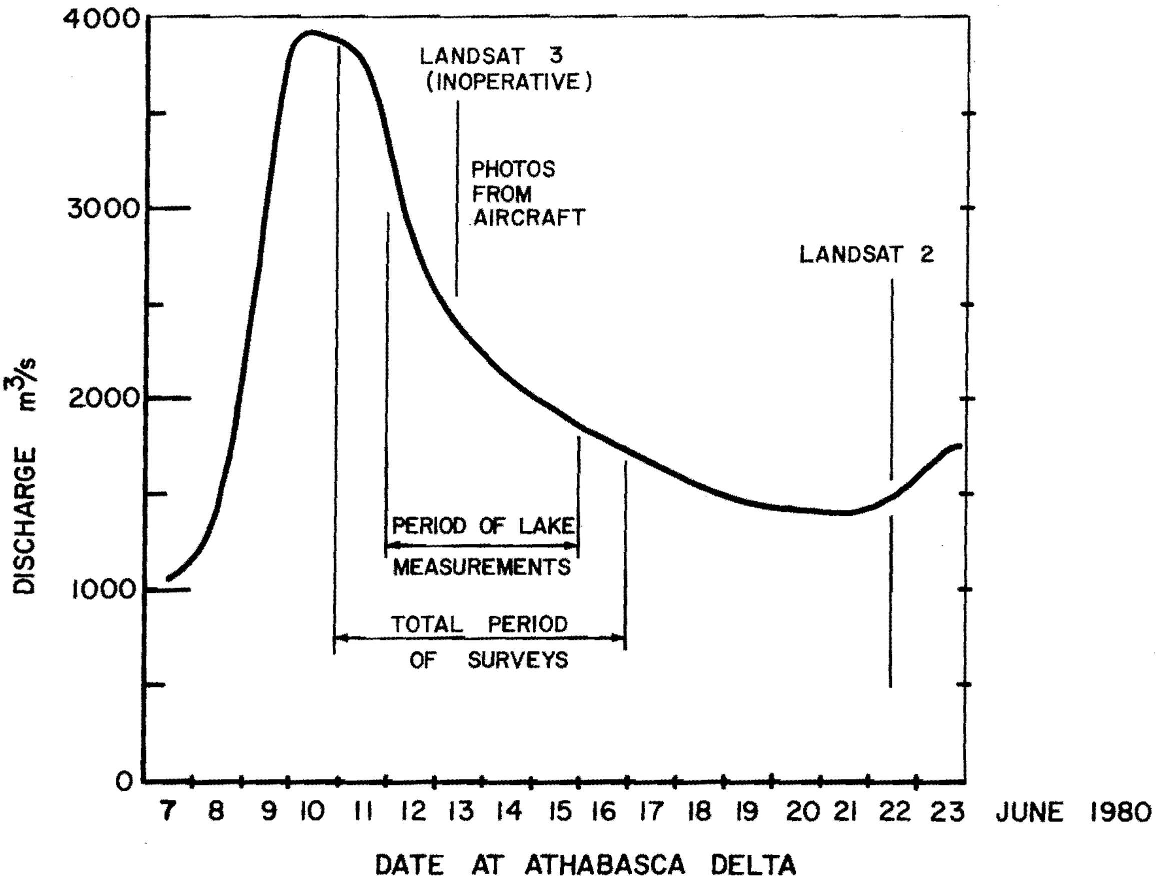


Figure 26. Athabasca River discharge hydrograph during June 1980 field program. Based on preliminary Water Survey of Canada data for gauge below Fort McMurray. Travel time to delta assumed to be one day.

Spot discharge measurements were also made as part of the field survey program, by current metering and cross-sectioning delta distributaries and lake outflow channels. These data are shown along with other channel data in Table 16. Adjusted to a common date of June 12, the distributary channel data indicate a total inflow of about 2700 m^3/s, compared with about 2900 m^3/s indicated by Figure 26.

Outflow channel discharge measurements shown in Table 16, adjusted to a common date of June 13, indicate a total outflow of about 1350 m^3/s, which checks reasonably with differences between Slave River flows at Fitzgerald and Peace River flows at Peace Point.

Weather during the survey period was generally good. Local wind observations at lake sampling points are listed with other survey data in Table 17. Selected wind data from Fort Chipewyan airport, listed in Table 18, show considerable variability in speed and direction. Comparison of these observations with simultaneous Fort Chipewyan data shows considerable discrepancies in some cases: it is clear that the Fort Chipewyan station is not a reliable guide to conditions on the lake. For the most part, wind directions were from 90^0 to 270^0, that is from east through south to west. On June 13 when the wind was blowing strongly along the lake from the northeast, survey operations were prevented by wave conditions.

6.3.3 Channel and Lake Sampling

Two boats and field crews were used to collect the channel and lake data listed in Tables 16 and 17 respectively. Lake data points are mapped in Figure 20. Point coordinates were determined by means of a Del-Norte "Trisponder" position-fixing system, using two shore units and a boat unit. As well as the lake data points, Figure 20 also shows the approximate locations of five continuous depth and conductance profiles.

The principal parameters measured at lake and channel sampling points were as follows:

- water depths;
- current and wind velocities;

Table 16. Data from channel surveys, 10-16 June 1980.

Location	Date	Discharge	Surface Width	Mean[1]/max. depth	Mean velocity	Specific conductance	Secchi depth	Suspended sediment		Bed material	
								concentration[2]	median dia.	median dia.	% sand
		m^3/s	m	m	m/s	µS/cm	m	mg/L	mm	mm	
Athabasca R. nr. Embarras Airport	10 June 17 June	4000 1700	400 400	7.7/8.5 4.7/5.5	1.3 0.9	240[3] 220[3]	0.04 --	1030 (1 m) 700 (1 m)		-- --	-- --
Embarras R. nr. mouth	11 June	780	94	5.7/7.0	1.45	240[3]	0.03	2200	--	0.01	5
Fletcher Ch. nr. mouth	15 June	170	161	2.0/3.4	0.54	220[3]	0.05	1000	--	0.07	50
Goose Is. Ch. nr. mouth	12 June	990	187	4.1/5.5	1.30	240[3]	--	7700	--	0.02	10
Big Point Ch. nr. mouth	12 June	620	156	3.6/4.5	1.09	240	0.025	2500	0.0036	0.04	30
Riv. des Rochers below inlet	13 June	1140	530	5.3/7.8	0.40	240 (see Fig. 25)	--	1350	0.003	0.015	12
Quatre Fourches NE fork	16 June	410 (from Lake Ath.)	132	3.8/5.2	0.81	275	0.05	1200	--	0.025	<1
Quatre Fourches NW fork	16 June	240 (to Peace R.)	146	3.2/3.8	0.52	--	0.04	3000	0.004	0.02	5

[1] Mean depth = cross-sectional area/surface width

[2] Depth-integrated except for Athabasca River (1 m depth).

[3] Lab. reading reduced to accord with field readings - see text section 6.3.3.

Table 17. Data from lake surveys, 12-15 June 1980.

Location No. (see Fig. 20)	Date	Depth to bottom m	Current data			Wind data		Specific conductance µS/cm	Secchi depth m	Suspended sediment		Bed material median dia. mm
			depth m	speed m/s	direction[1] degrees	speed m/s	direction[1] degrees			Concentration mg/L (depth m)	Median dia. mm	
Big Point - Bustard Island												
J1	14 June	1.5	0.2	0.88	185	7.2	165	--	0.03	1980 (1.0)	0.003	--
			0.7	0.78	205							
			1.0	0.79	205							
			1.3	0.57	195							
J2	14 June	1.0	0.2	0.46	215	6.7	195	--	0.03	1660 (0.5)	--	0.07
			0.4	0.42	200							
			0.6	0.38	210							
			0.8	0.30	215							
J3	14 June	1.2	0.2	0.15	270	4.6	225	220[2]		--	--	--
			0.5	0.14	225							
			0.7	0.16	235							
			1.0	0.15	235							
J4	14 June	2.3	0.2	0.12	245	4.6	235	--	0.03	940 (1.0)	--	.016
			0.8	0.11	245							
			1.5	0.08	225							
			2.1	0.05	175							
J5	14 June	2.8	0.2	0.10	215	5.2	215	220	0.04	--	--	--
			1.0	0.09	215							
			1,8	0.06	185							
			2.6	0.05	195							
J6	14 June	2.5	0.2	0.12	195	1.8	225	205	0.04	790 (1.0)	0.0023	--
			0.8	0.10	175							
			1.6	0.07	195							
			2.3	0.04	220							
J7	14 June	2.6	0.2	0.10	165	calm	--	200	0.04	--	--	--
			1.0	0.09	185							
			1.7	0.09	195							
			2.4	0.04	195							
J8	14 June	2.9	0.2	0.10	180	calm	--	215	0.03	720 (1.0)	--	0.006
			1.1	0.08	195							
			1.9	0.08	190							
			2.7	0.05	195							
Goose Is. - Pte. Basse												
J14	15 June	0.7	0.2	0.10	140	1.5	30	--	0.06	760 (0.5)	--	0.076
			0.35	0.07	160							
			0.5	0.09	190							
J15	15 June	1.0	0.2	0.11	160	3.1	45	210[2]	0.05	--	--	0.02
			0.5	0.10	135							
			0.8	0.06	150							
J16	15 June	1.1	0.2	0.12	160	3.6	65	--	0.05			
			0.55	0.11	165							
			0.9	0.07	165							
J20	12 June	2.2	0.2	0.07	135	calm	--	280	0.10	330 (1.0)	--	--
			1.0	0.03	215							
J11	14 June	2.4	0.2	0.05	75	calm	--	--	0.05	370 (1.0)	--	0.016
			0.8	0.04	115							
			1.5	0								
			2.2	0								
J18	12 June	2.5	0.5	<0.02	?	calm	--	110	0.32	(1.0)	0.0023	--
J12	14 June	2.5	0.2	0.07	75	1.0	225	--	0.25	160 (1.0)		0.006
			0.9	0.05	105							
			1.6	0.04	90							
			2.3	0.02	85							
J17	12 June	2.5	0.5	0.04	115	0.5	45	110	0.22	--	--	0.009
			1.0	0.03	80							
			1.5	0.03	100							
J13	14 June	2.5	0.2	0.03	95	1.0	180	--	0.26	90 (1.0)	--	0.008
			0.9	0.08	90							
			1.6	0.07	120							
			2.3	0.04	115							
W. of Embarras R. mouth to Fort Chipewyan												
J21	15 June	0.4	0.2	0.08	125	2.0	285	--	0.05	560 (0.2)	--	0.067
J22	15 June	0.8	0.2	0.12	165	2.6	265	210[2]				0.073
			0.6	0.10	150							
J23	15 June	0.9	0.2	0.14	90	6.2	80	--	0.05	520 (0.5)	0.0023	0.03
			0.45	0.13	90							
			0.7	0.12	90							
J24	15 June	2.2	0.2	0.28	110	4.1	90	--	0.05	510 (1.0)	--	0.033
			0.8	0.27	110							
			1.4	0.25	115							
			2.0	0.16	115							
J27	12 June	7.0				1.0	300	180	--	30 (1.0)	--	0.012
J25	15 June	4.7	0.2	0.57	85	3.6	70	--	0.23	230 (1.0) 110 (3.7)	--	0.012
			1.7	0.55	85							
			3.1	0.39	85							
			4.5	0.32	85							

---

[1] Indicates direction from which current or wind was moving, referred to north as 0°. Data obtained at 2 m height using hand-held anemometer.

[2] Lab reading reduced to accord with field readings - see text Section 6.3.3.

Table 18. Fort Chipewyan wind data, 9-16 June 1980

Date	Time	Speed m/s	Source Direction Degrees from North
June 9	8 am	3.5	190
	noon	4	190
	4 pm	7.5	260
10	8 am	2	260
	noon	3.5	300
	4 pm	5	310
11	8 am	2.5	310
	noon	2.5	270
	4 pm	4	320
12	8 am	1.5	260
	noon	2	300
	4 pm	0	
13	8 am	3.5	70
	noon	7.5	70
	4 pm	3.5	70
14	8 am	2	160
	noon	4	170
	4 pm	6.5	210
15	8 am	2	10
	noon	2	110
	4 pm	5.5	240
16	8 am	4	50
	noon	7.5	40
	4 pm	4.5	70

- specific conductance;
- Secchi depth (transparency);
- suspended solids and bed materials.

At the channel measuring points, velocities were measured with a Price current meter and depths with an echo-sounder at a number of verticals, to allow calculation of approximate discharges. Depth-integrated suspended sediment samples and bed-material samples were also obtained.

At lake sampling points, current velocities were measured by an electro-magnetic directional current meter, and wind velocities by a hand-held anemometer at 2 m height. Specific conductance was measured at some points by a field meter and at others by later analysis of water samples. Transparency was measured as the depth to visual extinction of a 20 cm diameter white disc (Secchi disc). Suspended solids concentration and grain size were determined by laboratory analysis of water samples, mostly from a depth of 1 m. Bed material samples were collected with a drag bucket and analyzed for grain size.

Lake current data from Table 17, mostly from 14-15 June, are plotted in Figure 27. These indicate the following characteristics:

- an expanding jet running north from Big Point Channel towards Bustard Island, with velocities diminishing from nearly 1 m/s just off the channel mouth to about 0.1 m/s at 8 km north of the delta shoreline;
- north from Goose Island, a current flowing from the south to southeast, with velocities of about 0.2 m/s;
- southwest of Bustard Island, a weak lake current flowing generally from the east, with velocities of about 0.05 m/s;
- near the lake outlet southeast of Fort Chipewyan, a current flowing from the east (towards the outlet) with velocities in the range of 0.25 to 0.6 m/s.

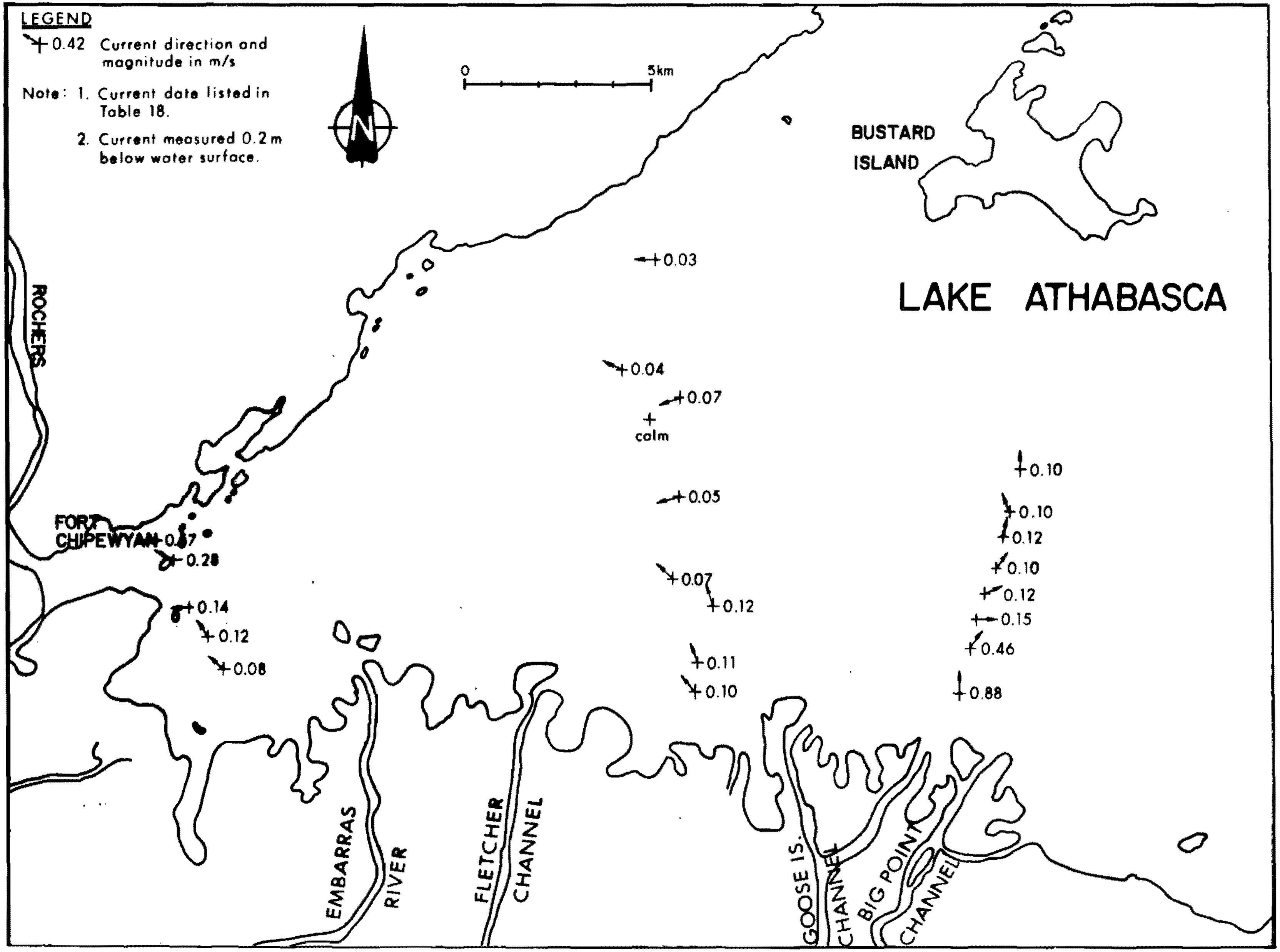


Figure 27. Map of lake current data 14 and 15 June 1980.

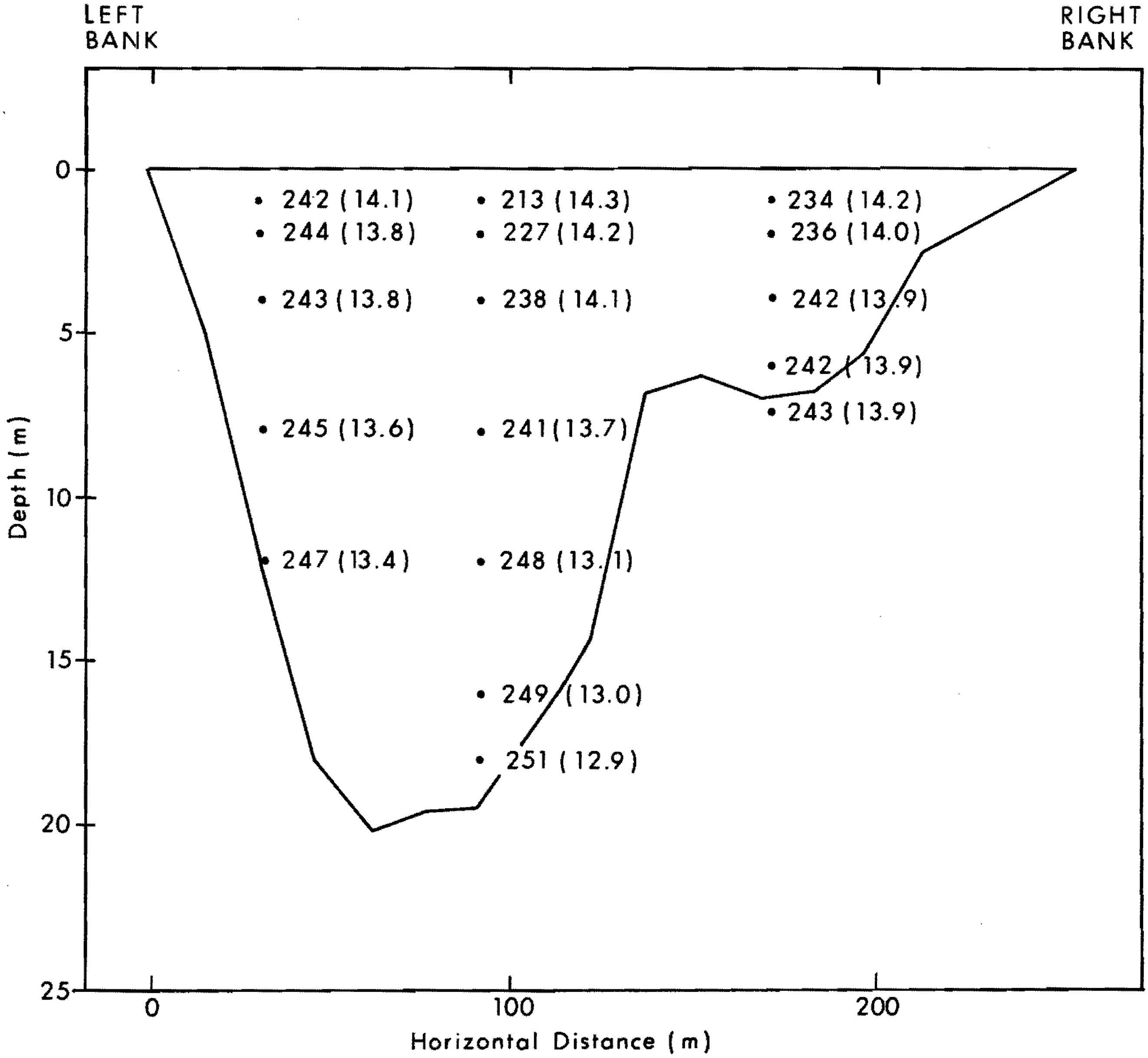
Secchi depths in the channels and in that part of the lake occupied by Athabasca River inflows were approximately 0.05 m. In Lake Athabasca beyond this zone, values were approximately 0.25 m. The low transparencies are due to high suspended sediment concentrations.

A slight difficulty arose over specific conductance values, in that some were read directly in the field and others determined later from water samples. Where readings overlapped, sample values appeared to be about 30% greater. Sample values have therefore been adjusted downwards to provide a common basis. Generally, values were around 250 S/cm in the Athabasca River and inflow channels, and around 100 S/cm in lake water unaffected by river inflow. These values are very similar to previous open water readings shown in Figure 23.

Figure 28 shows cross-sectional conductance and temperature distributions at the lake outlet on June 13. Near the bottom, temperature was about 13^{o} C and conductance about 250 S/cm, the same as river water. At the surface, temperature was over 14^{o} C and conductance was about 210 S/cm in midstream and about 240 S/cm near the banks. These data indicate that the outflow consisted mainly of river water; this could be expected from the hydrologic data of Table 13 and Figure 26, which indicate that on the date in question river inflow exceeded lake outflow. It appears, however, that at the lake outlet there was a central surface stream which included some admixed Lake Athabasca water, presumably drawn in from the area between Bustard Island and Fort Chipewyan. Visual indications of this movement can in fact be seen in color infrared photographs (Figure 32).

Spatially uniform conductance and temperature distributions were found at a point 20 km downstream of the lake outlet in the Riviere des Rochers. This indicates that complete mixing of lake and river waters had been achieved, confirming the assumption made in the water quality analysis of Section 5.2.

Suspended sediment concentrations in the inflow channels on 12 June were about 2500 mg/L, and by 15 June had apparently fallen



Legend: 245(13.6): Spec. conduct. μS/cm (Temp. °C)

Figure 28. Cross-section at outlet of Lake Athabasca showing conductance and temperature distributions on 13 June 1980.

to about 1000 mg/L. On 14-15 June, when most of the lake samples were taken, inflow concentrations were probably between 1500 and 1000 mg/L. In Lake Athabasca, concentrations diminished with distance from the channel mouths. In lake water north of the zone of river inflows, concentrations appear to have been about 100 mg/L. In the outlet channels, values appear to have been around 1200 to 1400 mg/L (Table 16). An anomalously high value was obtained in the northwest fork of Quatre Fourches Channel.

Figure 29 shows a plot of approximate conductance and sediment concentration values superimposed upon an enlarged LANDSAT Band 6 image from 22 June 1980, which essentially presents a near-surface picture. Images in Bands 4, 5 and 6 are compared in Figure 30; Band 6 presents the sharpest tonal discrimination. It is tempting to infer correspondences between the tonal patterns and the sediment concentrations. This would be misleading, however because other evidence shows that patterns had changed somewhat between 14-15 June, when most of the data were taken, and 22 June, the date of the image. As can be seen in Figures 31 and 32, on 13 June the zone of lighter (silty) water finished perhaps 5 km south of Bustard Island: as the Athabasca River flood hydrograph receded from then on (Figure 26), the zone of silty river water in the lake apparently spread north to Bustard Island. Interpretation of the LANDSAT tonal patterns is discussed further in Section 6.3.5.2.

Depth profiles and conductance/depth profiles along lines plotted in Figure 20 are shown in Figures 33 and 34. Notable features are (i) the very flat slope of the delta front, approximately 0.3 m per km; (ii) the deep channel near the north shore east of Fort Chipewyan; (iii) a sharp drop in conductivity at the edge of the deep channel on 14 June 1980; and (iv) less abrupt drops in conductivity on profiles C2 and C3.

Bed materials sampled near the mouths of the Athabasca inflow channels (Table 16) had median grain sizes varying from 0.01 to 0.07 mm, with proportions of fine sand (0.06 mm) varying from 5% to 50%. In Lake Athabasca, median grain sizes reduced to 0.006 mm at a distance of 8 km north of the delta shoreline. Figure 35 shows

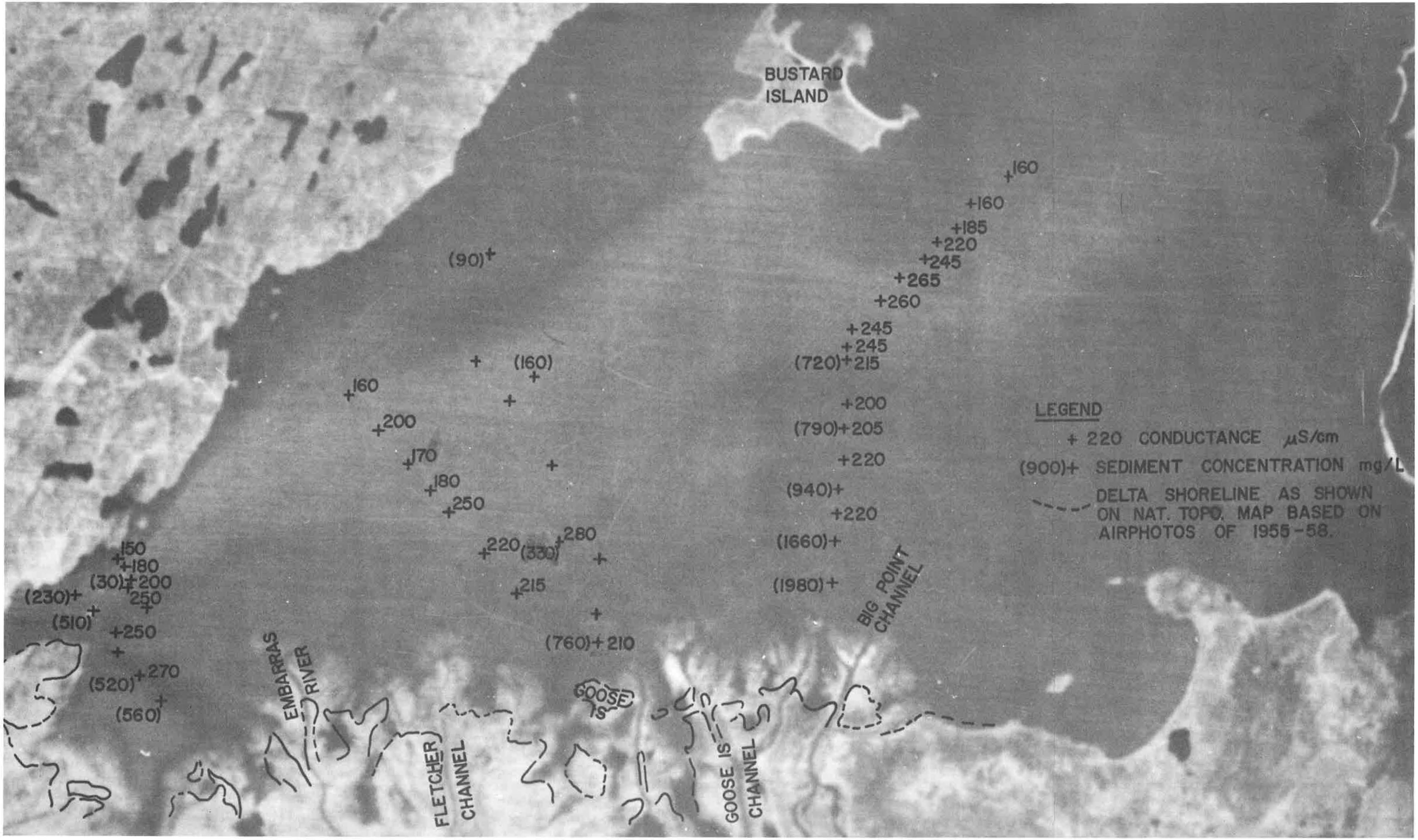


Figure 29. Conductance and sediment concentration data of 12 to 15 June 1980 superimposed on LANDSAT Band 6 image of 22 June 1980.

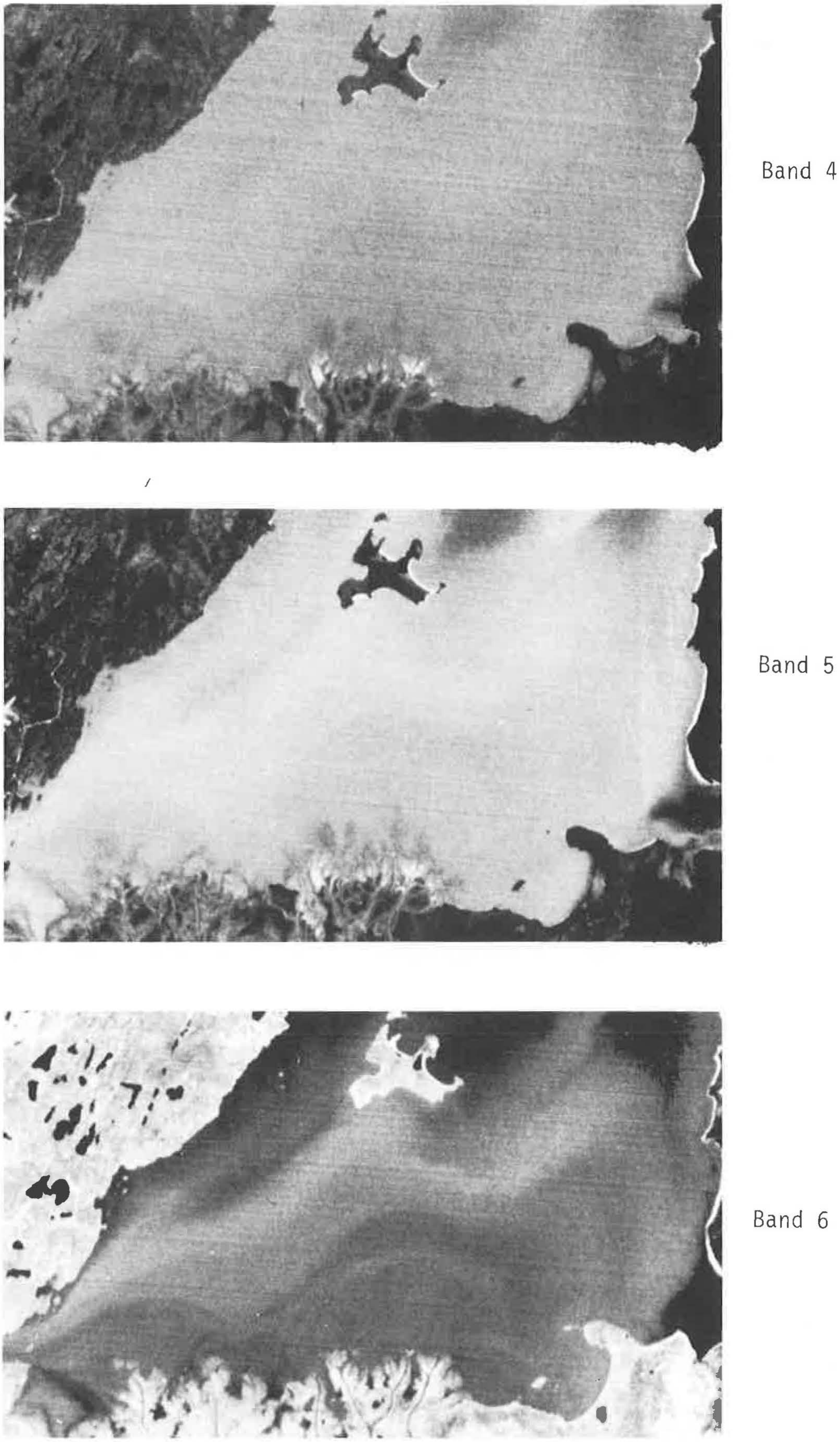


Figure 30. LANDSAT images from 22 June 1980 in three spectral bands.

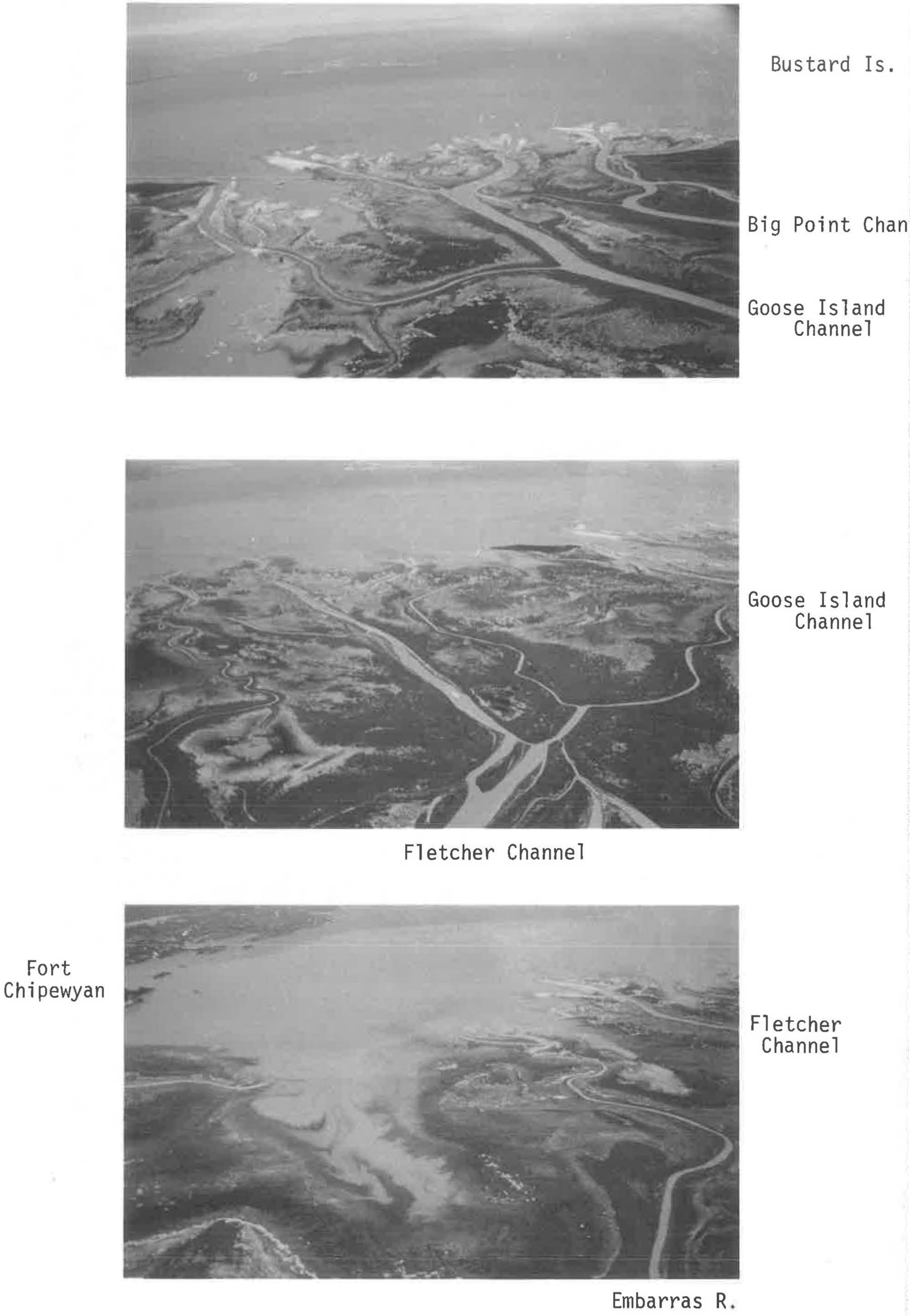
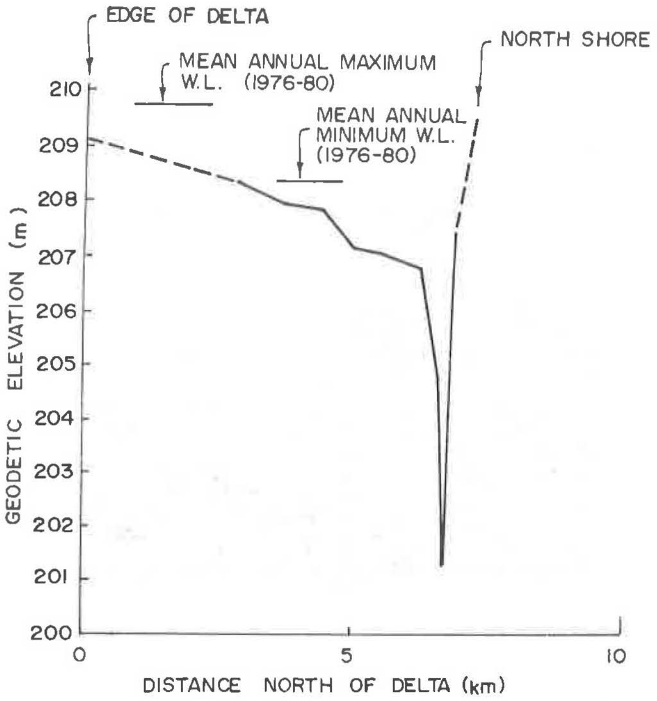


Figure 31. Panoramic series of color infrared photographs looking north to northwest from Athabasca Delta 13 June 1980.

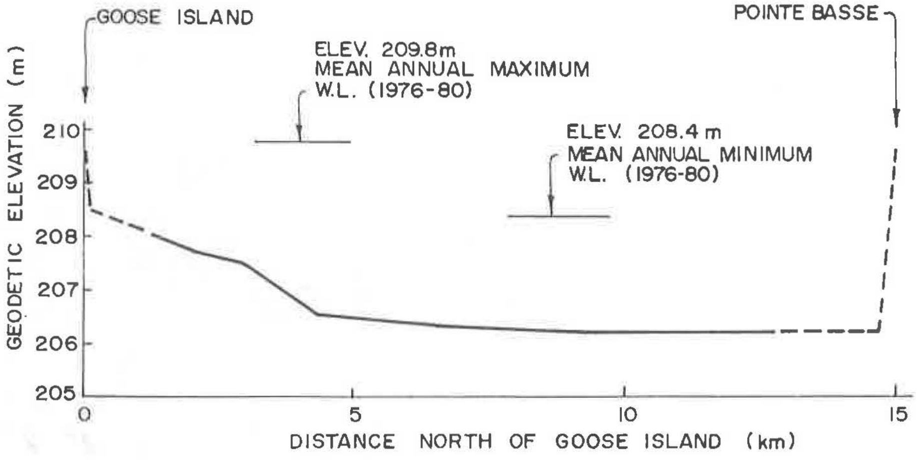
a) looking east

b) looking southwest

Figure 32. Color infrared photographs near Fort Chipewyan 13 June 1980.



Profile D1



Profile D

Figure 33. Depth profiles along lines D1 and D2 (see Figure 20 for locations).

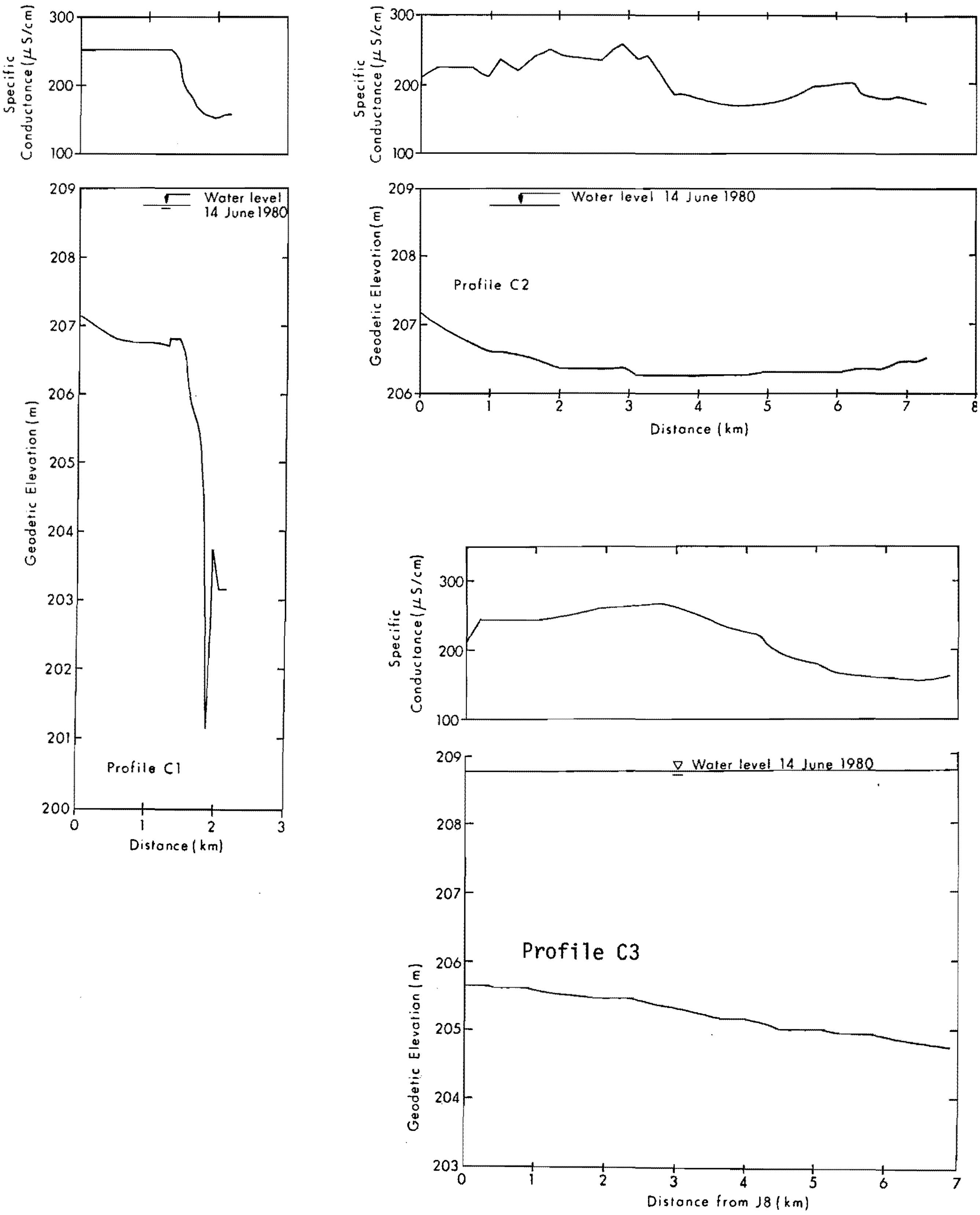
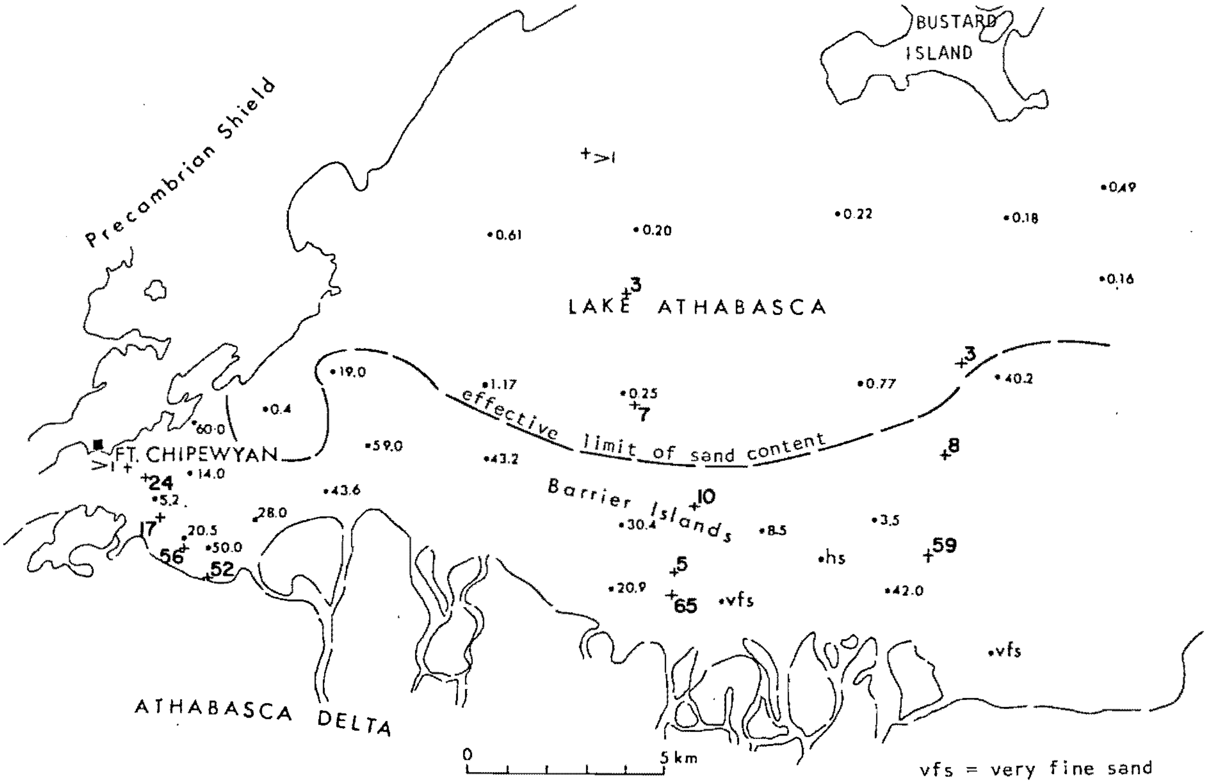


Figure 34. Conductance and depth profiles on 14 June 1980 along lines C1, C2 and C3 (see Figure 20 for locations).



Legend: ·20.9 data by Bayrock and Root, 1973 (Figure 11)

+ 65 data from 1980 field program

Figure 35. Percentage of sand in bottom samples from Lake Athabasca: 1980 data compared with 1973 data of Figure 11.

percentages of sand in bottom samples superimposed on Bayrock and Root's (1973) data (Figure 11).

6.3.4 Drogue and Dye Experiments

Three biplane drogues were released in the mouths of the major distributary channels to determine the time of travel of Athabasca River water through the south end of Lake Athabasca. The drogue vanes were set 0.5 m below the surface. Only one of the three drogues was retrieved: this one was released at 1800 hr on 12 June in the east branch of Goose Island Channel and retrieved at 0900 hr on 14 June in Fort Chipewyan Bay. It travelled approximately 25 km in 39 hours or less, at an average speed of 0.18 m/s or greater.

The travel speed of this drogue is much greater than would be expected from the current data shown in Table 17 and Figure 27, partly because the current data post-date the period of drogue travel. On 13 June, when probably most of the travel took place, there was a strong wind from the east (see Table 18). Assuming an average wind speed of 6 m/s, and a current speed equal to 4% of wind speed, a surface current of 0.24 m/s would be predicted. It therefore seems likely that the high travel rate of the drogue was caused mainly by a wind current on 13 June.

Two dye experiments were conducted during the field program. The first was planned to coincide with and hopefully to be recorded by the LANDSAT 3 satellite overpass at noon on June 13. A 15 kg slug of Rhodamine WT fluroescent dye was injected from a floatplane into Goose Island Channel at 11:45, approximately 1 km upstream of the mouth. It was planned to track the dye in Lake Athabasca, using a boat to criss-cross the dye cloud. The boat was mounted with a flowthrough fluorometer and pump, the output from the fluorometer being recorded on a chart, and positions were to be fixed using the Trisponder position-fixing system. The parameters of interest would have been the rate of travel and the spread of the dye cloud. Unfortunately, strong winds from the northeast made boat travel on the lake hazardous due to wave conditions. Nevetheless, the dye test was proceeded with in the hope of obtaining a satellite image and possibly of locating and tracking the dye the next day.

As previously noted, no imagery was recorded during the June 13 satellite overpass. Attempts to locate the dye on June 14 were unsucessful. One interesting feature became apparent, however, during the search for the dye, in that natural background fluorescent concentrations of Athabasca River water and Lake Athabasca water were quite distinct and essentially followed the same patterns as variations in specific conductance. Therefore background fluorescence can also be used to identify the two waters.

The second dye experiment was conducted on June 15 and involved injection of a 15 kg slug of dye into Lake Athabasca at a point approximately 14 km east and 3 km north of Fort Chipewyan (point J12 on Figure 20). The depth of water at this point was 2.75 m. It was hoped to obtain measurements over an 8-hour period, but wind conditions over this period were variable, with speeds from calm to 8 m/s and directions from 30^0 to 120^0, making interpretation of data for the whole period difficult: ideally, the wind should remain steady over the whole test period.

The condition of steady wind was approximately achieved for the first 3 hours of the test. The dye was injected at 11:47 hr, but for the first two hours dye concentrations were too large to be measured by the fluorometer and only visual estimates of cloud size could be made. Typically the shape of the dye cloud was elongate in the direction of the wind, resembling an ellipse. Figure 36 shows measured concentration contours for the dye cloud at 14:56 hr, approximately 3 hours after injection. The time taken to obtain these contours was approximately 10 minutes and the concentration distribution can therefore be assumed for practical purposes to be instantaneous.

It was hoped that the second dye test would give an indication of diffusivities in the main part of the southwest end of Lake Athabasca. These could then have been used with confidence in a circulation model of the lake. However, because of the unsteady wind conditions, the diffusivities that are calculated (see 6.3.5.3) can only be considered as crude estimates.

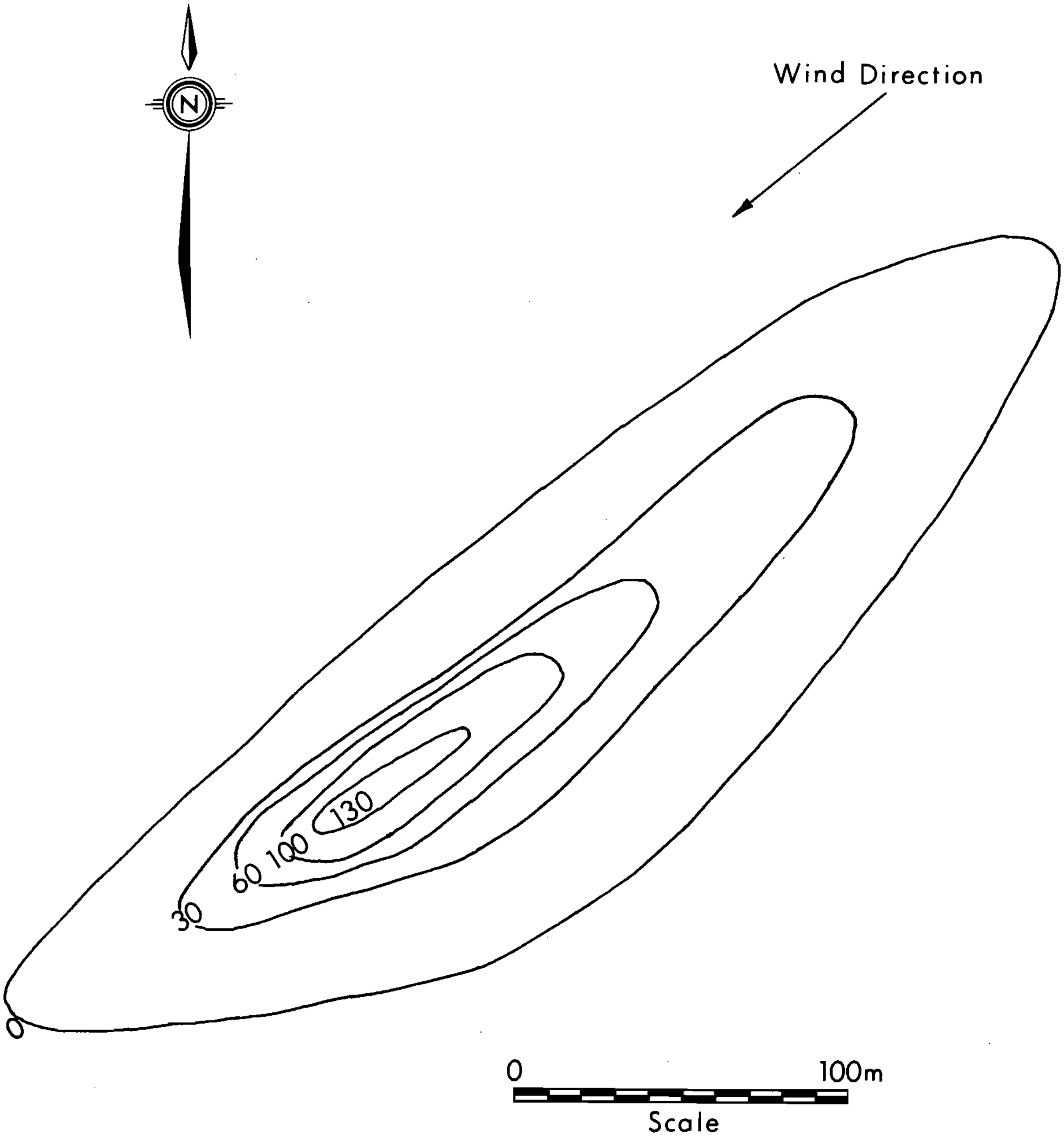


Figure 36. Plan of dye concentrations after 3 hours in test of 15 June 1980 (μg/L).

6.3.5 Discussion of Results

6.3.5.1 Sediment Balance

Consideration of the sediment balance during the 1980 survey period is somewhat complicated by the peaking of an unusually high flood at the beginning of the period. An approximate balance for the 10-day period 9-18 June 1980, which appears to cover most of the direct flood runoff part of the hydrograph (Figure 26) has been analyzed by graphical interpolation and extrapolation of data listed in Table 16. Results are shown in Table 19: over the 10-day period it appears that sediment outflow from Lake Athabasca was about 42% of sediment inflow from the Athabasca River. This result may be compared with Table 7, which showed outflow percentages of 79%, 55% and 61% respectively for years 1973, 1975 and 1976. It is evident from Table 19 that continuation of the balance over a longer period would result in a considerably greater outflow percentage, because in the latter part of the tabulation sediment outflows are considerably in excess of inflows.

Limited data on sediment grain sizes contained in Tables 16 and 17 suggest that the median grain size of outflow sediment (approximately 0.003 mm) was only marginally smaller than that of inflows. A comparison of grain size distributions (Table 20) shows however a more noticeable change in the coarser fractions: for example, the proportion of material coarser than 0.01 mm reduced from about 14% in the inflow to about 7% in the outflow. These distributions are much finer than the average Athabasca River distribution shown in Table 8, which has a median grain size about 5 times larger. It therefore appears that in June 1980 the coarser fractions of the Athabasca River sediment were being deposited in the delta distributaries as well as in Lake Athabasca.

6.3.5.2 Interpretation of LANDSAT Images

The plot of lake sediment concentrations of 14-15 June on top of the Band 6 LANDSAT image of 22 June (Figure 29) appears at first sight to show some pecularities. The zone of lighter tone to

Table 19. Sediment balance for flood inflow period 9-18 June 1980.

Date	Inflows from Athabasca R.			Outflows from L. Athabasca		
	water discharge m^3/s	sediment concentration mg/L	sediment discharge t/day	water discharge m^3/s	sediment concentration mg/L	sediment discharge t/day
9	3000	700	181 000	400	200	7 000
10	3900	1000	337 000	400	300	10 000
11	3800	2500	820 000	430	400	15 000
12	2900	1700	678 000	970	800	67 000
13	2400	1900	393 000	1610	1350	188 000
14	2100	1400	253 000	1790	1400	217 000
15	1900	1000	164 000	1830	1350	213 000
16	1800	800	125 000	1820	1300	211 000
17	1700	700	103 000	1900	1250	205 000
18	1600	600	83 000	1850	1200	192 000
		10-day total	3 137 000			1 325 000

Ratio outflow/inflow = 1325/3137 = 0.42.

Table 20. Grain-size distribution in inflow and outflow sediment, 12-13 June 1980[a]

Grain diameter mm	Inflow - Big Pt. Channel % Coarser	Outflow - Riviere des Rochers % Coarser
0.001	92	90
0.002	71	66
0.004	45	38
0.006	30	20
0.008	20	12
0.01	14	7
0.02	2	1
0.04	0.1	0.1

[a] Based on analyses by Chemical and Geological Laboratories Ltd.

the south and southwest of Bustard Island appears to correspond to relatively low sediment concentrations, with darker (clearer?) water to the north and darker (siltier?) water to the south. This is not in accord with most information in the literature, which implies a direct monotonic relationship between image brightness and sediment concentration up to relatively high concentrations. Taking into account, however, the color infrared photographs of 13 June (Figures 31 and 32), and considering the continuing decline in river inflows after 13 June (Figure 26), it appears possible that the light band in Figure 29 is in fact a zone of high sediment concentrations, which has been pushed offshore by succeeding clearer inflows. It nevertheless seems likely that the zone of darker tone near the delta shoreline has sediment concentrations many times greater than the zone of similar tone west of Bustard Island. A similar difficulty arises over the images of 1/2 July 1975 (Figure 18C) discussed in Section 4.3, and in that case it is practically certain that the darker river water contained higher sediment concentrations than the lighter lake water to the north (Table 9).

The plot of specific conductances in Figure 29 also shows the highest values several km north of the delta shoreline. It appears likely that the flood inflow of 10-12 June had pushed out a zone of slightly higher conductance resulting from earlier river inflows.

6.3.5.3 Mixing

From the dye concentration distribution shown in Figure 34 it is possible to estimate the longitudinal and transverse spatial variances as $S_x^2 = 4000 \text{ m}^2$, $S_y^2 = 200 \text{ m}^2$; where S_x and S_y are standard deviations of the distribution in the longitudinal direction (along the major axis of the dye cloud) and in the transverse direction. The time from injection is 11340 seconds, therefore the effective longitudinal and lateral diffusion coefficients can be estimated as:

$$K_x = \frac{1}{2} \frac{d(S_x)^2}{dt} = 1760 \text{ cm}^2/\text{s}; \quad K_y = \frac{1}{2} \frac{d(S_y)^2}{dt} = 90 \text{ cm}^2/\text{s};$$

No estimate of vertical diffusivity can be derived from the experiments because it is assumed that complete mixing was established in the vertical direction in a short period of time. This assumption is reasonable considering the shallowness of the lake at the point of measurement.

The elongate nature of the dye cloud indicates that the vertical velocity gradient was responsible for increased effective dispersion in the direction of the wind. The surface current velocity was calculated as 6.2 cm/s from observed time of travel. The mean vertical velocity gradient is thereby estimated as

$$\frac{dv}{dz} = \frac{6.2 \text{ cm/s}}{275 \text{ cm}} = 0.023 \text{ s}^{-1}$$

The vertical diffusivity can be estimated by a formula of Bengtsson (1978) as

$$K_z = 2 \times 10^{-5} \, hW$$

where h is the depth and W is the wind speed.

Assuming that the measured surface current represents 4% of the wind speed, the vertical diffusivity can then be estimated as:

$$K_z = 2 \times 10^{-5} \times 275 \times 6.2/0.04 = 0.85 \text{ cm}^2\text{/s}$$

If it is assumed that the longitudinal diffusivity (K_{xt}) due to turbulent diffusion alone (excluding dispersion due to velocity gradient) is approximated by the effective transverse diffusion coefficient (K_y) calculated above from the field data, then a longitudinal dispersion coefficient can be calculated according to the solution of Carter and Okubo (1965) for mixing in a uniform shear field. For $K_{xt} = K_y = 90$ cm^2/s, $K_z = 0.85$ cm^2/s and $dv/dz = 0.023$ s^{-1}, the calculated longitudinal dispersion coefficient is 1430 cm^2/s at t = 11340 seconds. This is reasonably close to the value of 1760 cm^2/s derived from the field data as given above.

7. SECONDARY STUDIES

In addition to the field investigations described in section 6, three secondary studies were conducted as part of Phase II in 1980. These were (i) a preliminary analysis of the velocity field, (ii) a consideration of the potential for modelling circulation and mixing, and (iii) a preliminary digital analysis of LANDSAT data from June 1980.

In considering the results of these secondary studies as described below, it should be realized that they were pursued only at a very preliminary level in order to indicate the directions in which more detailed studies might proceed. They should therefore be regarded rather as a preamble to further work than as part of the main study described in the foregoing sections of the report.

7.1 PRELIMINARY SEMI-EMPIRICAL ANALYSIS OF VELOCITY FIELD

7.1.1 General

The object was to conduct a few preliminary calculations of the velocity field at the southwest end of Lake Athabasca, using semi-empirical methods. A set of hydrologic conditions corresponding to 15 June 1980 was chosen for initial consideration. These were approximately as follows:

Inflows:	Big Point Channel	475 m^3/s
	Goose Island Channel	720
	Fletcher Channel	170
	Embarras River	420 (total inflow 1785)
Outflows:	Riviere des Rochers	1140
	Chenal des Quatre Fourches	410 (total outflow 1550)
Lake level:		208.75 m

For this flow event, field observations indicate that most of the lake outflow came from the Athabasca Delta inflows. Wind directions (Table 18) were such that the wind generated current or wind drift would tend to encourage the Delta inflows to proceed north to northeast in their original directions of entry into the lake, particularly the inflow from Big Point Channel. Consideration of this aspect, as well as the magnitude of the inflow velocities, indicated that the behaviour of the inflows might be analysed approximately using the theory of plane turbulent jets (Rajaratnam, 1976). The shallow depths off the delta and the turbulence in the river inflows indicate that vertical temperature or density differences can be neglected. The fineness of the bed material indicates that the effect of bed roughness on jet diffusion will be rather small and that the bed can be assumed essentially smooth.

If the bed shear stress beneath the jet is neglected, then its momentum flux can be assumed to be preserved. With this major assumption, the river discharge can be treated as a plane jet problem. Referring to Figure 37 the centerline depth-averaged velocity at any distance x from the river mouth, in the region of fully developed flow, is given by:

$$\frac{U_m}{U_o} = \frac{3.5}{\sqrt{x/b_o}} \qquad (1)$$

where U_o is the assumed uniform velocity at entrance to the lake and b_o is half the river width at entrance. The total width of the jet at any distance x is given by :

$$2\bar{b} \simeq 0.5\ x \qquad (2)$$

The limitations of these equations for the problem at hand are that they apply to an idealised plane jet with no vertical velocity gradient and that they assume no bed shear, which in practice will continuously reduce the momentum flux in the river inflow. Although there is little relevant experimental information available, a rough estimate based on somewhat related studies indicates that for x of the order of a few kilometres, the integrated bed shear stress is likely to be of the same order as the momentum flux in the river flow, hence Eq. (1) will seriously over-predict velocities and under-predict deflection of the inflow jets by lake currents. This

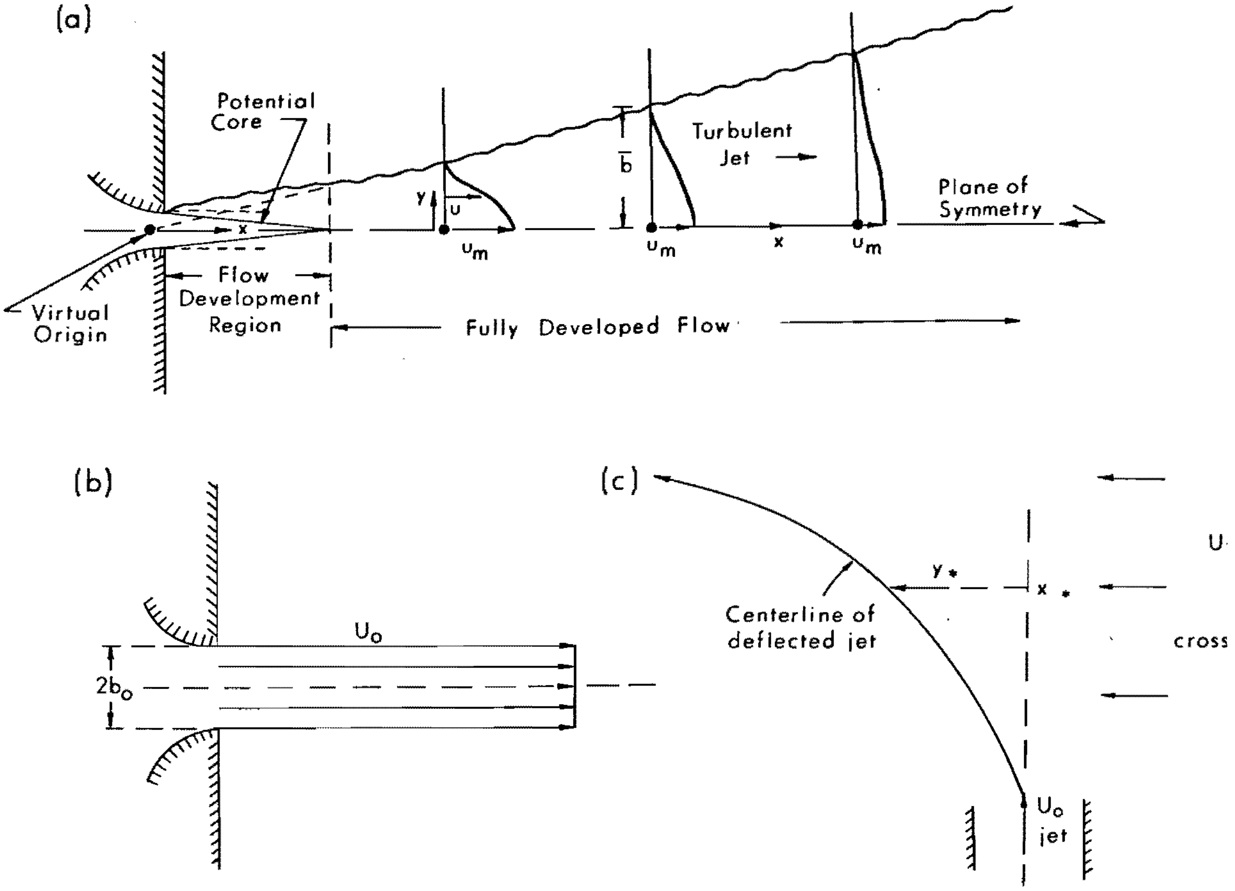


Figure 37. Definition sketches for plane turbulent jets
(a) half plan of free jet
(b) enlarged plan of initial conditions
(c) jet deflected by crossflow

aspect should be investigated further before making more definitive calculations: the necessary studies could be performed effectively in a hydraulic laboratory.

With regard to deflection of the inflow jets by lake currents, a model that is presently available (Rajaratnam 1976) has not been tested in comparable situations. Earlier results for a plane jet subjected to crossflow could be used to predict the deflections.

An order of magnitude analysis indicates that for channel entrance widths in the order of 160 m and entrance velocities in the order of 1 m/sec, the Coriolis force on the jet becomes important beyond a distance of about 8 km. In any more detailed study of regions well offshore from the distributary mouths, the Coriolis force should be considered.

7.1.2 Inflow from Big Point Channel

The objective is to plot the path of the inflow jet from Big Point Channel, accepting the assumptions and limitations discussed in 7.1.1. Locations J1 through J8 (Figure 20) lie approximately in the path of this plume. Hydraulic characteristics at the mouth of the channel are: discharge Q = 475 m^3/sec; outlet width ($2b_0$) = 156 m, outlet depth = 3.6 m, mean velocity = 0.85 m/sec, and lake level 208.75 m. Using Eqs. (1) and (2), values of the maximum velocity u_m, mean velocity V and total width 2b are given in Table 21.

At location J8, the horizontal eddy diffusivity in the jet is found to be 1.04 x 10^5 cm^2/sec (by Rajaratnam 1976) whereas the lake eddy diffusivity affecting the plume is about 2 x 10^4 cm^2/sec (by Csanady 1973). Thus the eddy diffusivity in the jet is about 5 times greater than that in the lake and hence the expansion of the plume as predicted above using jet theory should be reasonably valid, if pressure drag due to longitudinal bed slopes is neglected. Figure 38 shows the plotted expansion: it will be discussed further after the other plumes are calculated.

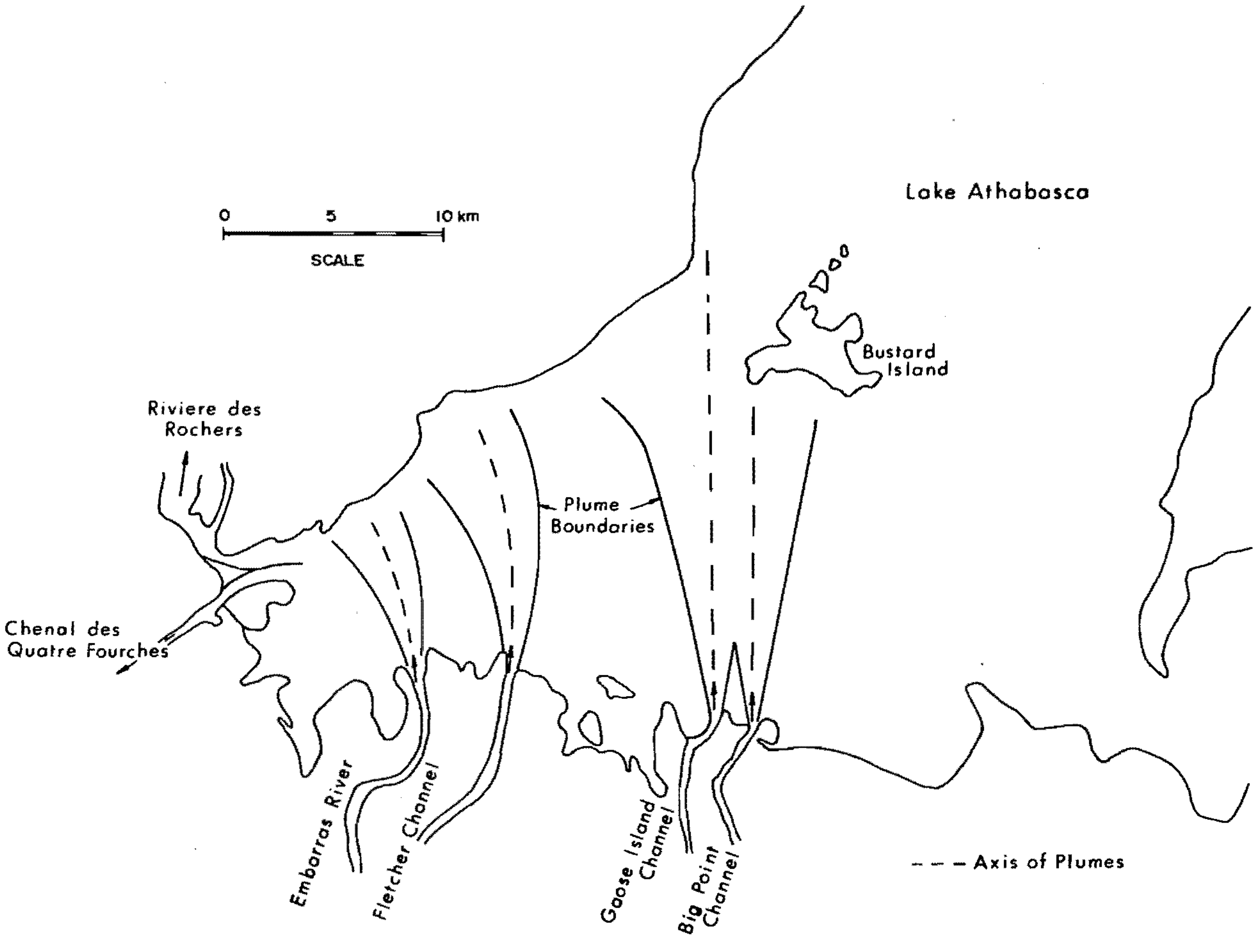


Figure 38. Calculated expansion of inflow jets in Lake Athabasca for conditions of 15 June 1980.

Table 21. Calculated quantities for jet expansion north of Big Point Channel, 15 June 1980

Distance from Channel Mouth m	Maximum Velocity U_m m/s	Mean Velocity V m/s	Jet_Width $2\bar{b}$ m/s
2750	1.51	0.75	1375
4000	1.25	0.63	2000
4875	1.12	0.56	2440
5625	0.49	0.25	2810
6250	0.46	0.23	3125
7000	0.44	0.22	3500
7625	0.42	0.21	3810
8875	0.39	0.20	4440

7.1.3 Inflows from Goose Island Channel, Fletcher Channel and Embarras River

For the initial portions of the plumes for which deflection was estimated to be negligible, calculations were performed using the same method as for Big Point Channel. Results for Goose Island Channel are given in Table 22.

Deflections due to crossflow of the plumes from Goose Island Channel, Fletcher Channel and Embarras River were calculated using the Volinsky-Abramovich method (Rajaratnam 1976). With reference to Figure 37, the axis of the deflected jet is given by the equation

$$\frac{C_d}{\alpha^2} \left(\frac{x_*}{\delta_o}\right) = 2 \sqrt{\frac{C_d \; y_*}{\alpha^2 \; \delta_o}} \qquad (3)$$

wherein (x_*, y_*) are the coordinates of the axis of the deflected jet, $\alpha = U_o/U_1$ where U_o is the jet velocity and U_1 is the velocity of the crossflow, C_d is a drag coefficient and δ_o is the thickness of the jet. Using a value of 2.0 for the drag coefficient, as suggested by Rajaratnam (1976), Eq. 3 reduces to

$$\frac{x_*}{\delta_o} = \sqrt{2} \; \alpha \sqrt{\frac{y_*}{\delta_o}} \qquad (4)$$

The plumes from the three inflows were calculated by Eq. 4 and the results are shown in Figure 38.

Considering Figure 38, the plumes from Big Point Channel and Goose Island Channel merge together within about 2 km of the channel mouths. The plume from Big Point channel appears to extend all the way to Bustard Island. The other three plumes, although deflected towards the west, appear to impinge on the north lake shore and to be guided by the shoreline. An important analytical omission is the cumulative effect on these plumes of bed shear,

Table 22. Calculated quantities for undeflected jet expansion north of Goose Island Channel, 15 June 1980.

Distance from Channel Mouth m	Maximum Velocity U_m m/s	Mean Velocity $\bar{V}$ m/s	Jet Width $2\bar{b}$ m/s
2000	2.44	1.22	1000
3000	1.99	1.00	1500
4000	1.72	0.86	2000
5000	1.54	0.77	1500
6000	0.65	0.33	3000
8000	0.56	0.28	4000
10 000	0.52	0.26	5000

which could reduce their velocities and hence result in greater deflection by the cross currents induced by the outflow from the lake.

7.1.4 Flow Distribution Near the Outlet of Lake Athabasca

For the flow event under consideration, the outflow discharges were 1140 m^3/s in Riviere des Rochers and 410 m^3/s in Chenal des Quatre Fourches. In the absence of detailed knowledge on turbulent flow distribution, it is a reasonable approximation to treat the converging outflow region as a zone of potential flow. For detailed predictions, the Laplace equation for velocity potential could be solved numerically. For preliminary purposes, a flow net can be drawn to indicate vertically averaged velocities, as shown in Figure 39. (These are based on an assumed average depth, whereas the depth in fact varies considerably in the outflow region.)

7.1.5 Discussion of Analytical Methods

The main limitation of the calculations on inflow jets appears to be the neglect of the effect of integrated bed shear on the momentum flux of the inflows. Preliminary estimates indicate that this could be significant and would make the plumes vulnerable to deflection by lake currents.

Another difficulty that would arise in analyzing the situation for other flow events is uncertainty over the magnitude and direction of the wind velocity. Farther away from the inflow channel mouths, wind generated currents could easily have velocities of the same order as velocities in the diffused inflow plumes.

7.2 POTENTIAL FOR MODELLING CIRCULATION AND MIXING IN LAKE ATHABASCA

Two modelling techniques are often used as aids to the solution of hydrodynamical problems: (i) mathematical modelling which solves differential or integral equations based on the physics of the flow system; and (ii) physical modelling, which uses scale models to observe the mechanics of the flow system. Both of these

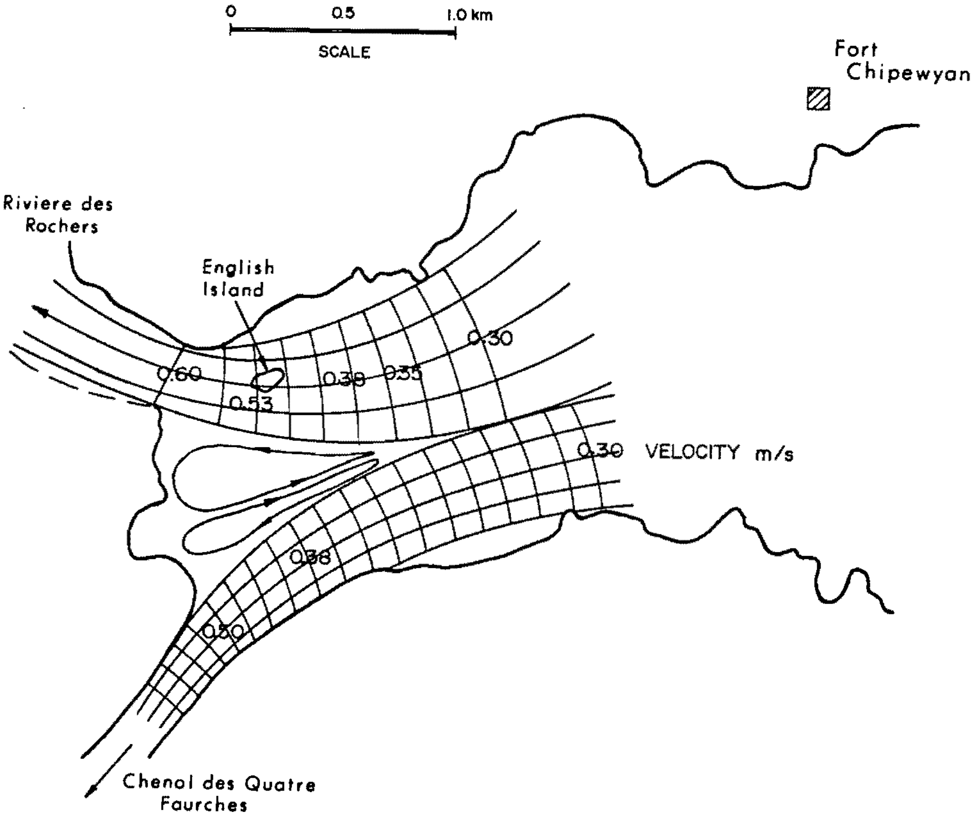


Figure 39. Flow nets for outflows from Lake Athabasca for conditions of 15 June 1980.

approaches will be discussed with reference to circulation and mixing in Lake Athabasca, especially the shallow region at the southwest end.

7.2.1 Mathematical Modelling

The starting point for all mathematical models is the Navier-Stokes differential equations of motion. These equations express basic physical laws: conservation of mass (continuity) and conservation of momentum (equations of motion). If heat transport and particulate transport are of interest, then two other similar equations can be formulated, the thermal energy equation and the conservation of species (species continuity) equation. The derivation of these equations can be found in fluid mechanics textbooks (see White, 1974 for example). These equations are quite general, but because of the complexity of even the simplest types of flow, a general solution is not possible. Therefore certain plausible simplifying assumptions are required before even attempting a solution.

Lake motions are almost invariably turbulent, as can be shown by calculating a Reynolds number for typical conditions. For a current velocity of only 10 cm/s and a lake depth of only 500 cm, the Reynolds number is approximately 5×10^5, which is well into the turbulent range.

The first simplification is concerned with the problem of randomly fluctuating turbulent flows. It is unrealistic to be able to predict the exact nature of these random fluctuations in time and space, so some type of averaging procedure is usually applied to the governing equations. The first average is a time average: any fluctuating variable is divided into mean and fluctuating components, and then substituted into the equations of motion. Averaging the resulting equations yields the so-called Reynolds equations describing the mean flow.

For example, the Reynolds equation for an incompressible fluid in the longitudinal direction is:

$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{v}\frac{\partial \overline{u}}{\partial y} + \overline{w}\frac{\partial \overline{u}}{\partial z} - f\,\overline{v}$$

(inertia terms) (Coriolis term)

$$= -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x} - \left\{ \frac{\partial}{\partial x}(\overline{u'^2}) + \frac{\partial}{\partial y}(\overline{u'v'}) + \frac{\partial}{\partial z}(\overline{u'w'}) \right\}$$

(pressure term) (turbulent stress terms)

where $\overline{u}$, $\overline{v}$, and $\overline{w}$ and u', v', and w', are the mean and fluctuating parts of the velocity field respectively, f is the Coriolis parameter given by $f = 2\Omega \sin\phi$ where Ω is the rotational speed of the earth and ϕ is the latitude, P is the average pressure, ρ is the density and x, y, z are the coordinate directions. The overbars represent time averages.

These equations express a balance between inertia forces, Coriolis forces, pressure forces and forces due to turbulent stresses. Molecular viscous stresses are neglected as being small compared to the turbulent stresses. This approximation is justifiable except near a solid boundary. Two other equations of motion in the transverse (y) and vertical (z) directions, along with the continuity equation, are available to solve for the four unknowns, $\overline{u}$, $\overline{v}$, $\overline{w}$, $\overline{P}$. However, the correlations like $\overline{u'^2}$ are not known, and additional equations are needed before a solution for the mean velocity field can be achieved. This is the closure problem of turbulence.

One method of closure is to relate the correlations to the mean velocity gradients by means of an eddy viscosity, in a manner analogous to molecular viscous stresses. For example (see Sunderman 1979) :

$$-\overline{u'v'} = A \left(\frac{\partial \overline{u}}{\partial y} + \frac{\partial \overline{v}}{\partial x}\right)$$

where A is the turbulent eddy viscosity. Field experiments are usually required for evaluation of A. This is done either by calibrating a hydrodynamic model against field data or by actually measuring the mean velocity gradients and correlations.

Recent theoretical models of turbulence are sometimes used to model the eddy diffusivity by relating them to characteristic quantities of the turbulence, for example kinetic energy and dissipation. Launder and Spaulding (1972) describe this approach.

In order to solve the governing equations of motion, boundary conditions must be prescribed at the geometrical borders of the lake including the water surface and lake bed. Most important is specification of the wind stress at the water surface, as this is often responsible for the motion. An empirical formula often used to calculate the surface stress is

$$\tau = \rho_a C_D W^2$$

where ρ_a is the air density, C_D is a drag coefficient and W is the wind speed at a given height above the water surface. The factor which has the greatest effect on the magnitude of the wind stress is the roughness of the water surface, quantified through the drag coefficient C_D. In general, for increasing wind speeds the surface roughness and drag coefficient increase. In a recent review, Bengtsson (1978) lists drag coefficients found by numerous investigators and quotes values in the range of 0.9 to 2×10^{-3}. Other boundary conditions, such as no flow through a solid boundary, and inflows and outflows, can easily be included in any numerical model. This then is the starting point for the first type of mathematical model, which utilizes the full three-dimensional set of Reynolds equations with experimentally determined eddy viscosities.

Dimensional analysis of the equations of motion is often helpful for determining the relative magnitude of each term in the equations. If it can be shown that one term is very much smaller than another term, simplification of the equations can justifiably be done. For example the Rossby number can be derived from such an analysis; for Rossby numbers that are small compared to unity, the inertia terms in the equation of motion can be neglected in comparison with the Coriolis force terms. For example, consider a very large lake where the horizontal dimension is $L = 100$ km and the velocity is $U = 15$ cm/s, then for latitude $0 = 50^{0}$ the Rossby number = $U/fL = 1.3 \times 10^{-2}$, which implies that the inertia terms can be neglected in the equations of motion. For smaller lakes or for larger velocities this may not be the case.

Another common simplification occurs in the equation for conservation of vertical momentum. For lakes much wider than deep (the usual case), the pressure gradient and gravitational force terms dominate the vertical momentum equation. Consideration of only these two terms results in the hydrostatic approximation (see for example Cheng et al 1976). The initial set of equations reduces to essentially a two-dimensional horizontal set with the vertical velocity specified from the continuity equation, although variations of the variables with respect to depth can still be considered.

The next problem encountered concerns the vertical density distribution and how it effects circulation and mixing in the lake. Water can be considered incompressible, and density differences are assumed only significant in relation to buoyancy force terms. As the density can be taken as a single-valued function of temperature, specification of the temperature field will specify the density distribution. This is somewhat complicated by the coupling that exists with the momentum equations and the thermal energy equation when buoyancy terms are included. Therefore for complete solution these equations must be solved simultaneously. However it is common practice to divide the lake into a series of layers, each of constant density, and to solve the equations of motion for each layer (see Simons 1973). For example a two-layered lake model is commonly formulated for the case of stably stratified deep lakes, the upper layer corresponding to the epilimnion and the lower layer to the hypolimnion. A one-layer model would be applicable to shallow lakes where the vertical density distribution is homogeneous, or nearly so.

From an order of magnitude analysis it can be shown that the vertical gradients of the turbulent velocity fluctuations are often much larger than their horizontal gradients. This is analogous to the situation for boundary layer flows where vertical gradients are much more significant than horizontal gradients.

Considerable simplification can be achieved for such flows, which in general are called "slender flows".

A further simplification that can be made is to integrate the equations of motion in the vertical direction. This is done over the entire flow depth for a homogeneous lake, or over the depth of each layer for a multilayered lake. The resulting equations are the so-called transport equations, containing components of the horizontal transport or depth-integrated volume flux (Csanady 1978). Coupled with a "slender flow" approximation, the depth integrated equations do not require specification of the troublesome turbulent fluctuation correlation terms. All that is required is the specification of shear stresses at the free surface and at the lake bed.

Although the governing equations have been simplified substantially by this stage, it is possible to demonstrate many observed features of lake circulation processes with these simplified models. Csanady (1978) reviews some of these models and shows that experimental evidence agrees reasonably well with their predictions within the framework of the assumptions involved. As was seen for the case of Ekman currents (Section 2.2), simplification of the governing equations of motion is a valuable aid to studying the characteristics of a single physical process. This approach is necessary because of the complex interaction between the many physical processes which contribute to lake circulation.

So far, only lake-wide circulation phenomena have been considered. For this case the lake is usually considered as a closed basin. Of special interest for the present study, however, are circulation phenomena near an inflow and outflow region. In the case of lake inflows, one appropriate model is that of a plane jet flowing into an ambient medium. Jet theories are well developed (Rajaratnam 1976) and can give reasonable results from very simple calculations. Outflow dynamics can be described by classical potential flow theory for the case of unstratified flow. Stratification however plays an important role in both inflow and outflow dynamics. Work along this line has been carried out for the effects of inflows and outflows on circulation and mixing in reservoirs. Fischer et al (1979) review this work for stratified inflows and outflows.

For lake-wide circulation models that use the full equations of motion, the effects of inflows and outflows on the general circulation pattern can easily be handled in the boundary conditions of the flow field. However in many lakes the effects of inflow and outflow do not significantly affect the lake-wide circulation. This is probably true of the main body of Lake Athabasca, but there is a region at the southwest end of the lake which is strongly affected by inflows and outflows. Any mathematical model of circulation in Lake Athabasca should therefore include the inflow and outflow in the analysis.

Recently, attempts have been made to utilize other types of averaging schemes to produce better lake models. Babajimopoulos and Bedford (1980) describe an approach in which they seek not only to reproduce the mean flow circulation but also the spectral statistics of the turbulence. This approach utilizes more sophisticated turbulence models than the eddy viscosity concepts more commonly used.

A sobering demonstration of some of the inadequacies of present lake circulation models was provided in a study of Lake Michigan by Allender and Saunders (1976). They made a statistical comparison of reliable field data against the predictions of three mathematical circulation models and a hypothetical 'model' which gave all velocities as zero. The zero circulation 'model' gave the smallest deviation in terms of least squares error.

Many authors in recent years have presented numerical solutions to the resulting equations for the problem of wind-driven circulation. Reviews of these methods are given by Cheng et al (1976), Sunderman (1979), Csanady (1978), Simons (1980), and Gallagher (1974). Basically two mathematical solution techniques are utilized, the finite difference method and the finite element method. The significant advantage of the finite element method is its ability to handle complex geometries. For simple geometries, either method is adequate.

Generally the success of any of the above models depends on the quantity and quality of field data available to verify the numerical results. Advances in the numerical treatment of the governing equations of motion have proceeded at a much greater rate than the acquisition of quality field data required to verify these models and its interpretation to explain the wide variations found in coefficients of eddy viscosity and diffusivity.

In conclusion, with regard to mathematical modelling of circulation in Lake Athabasca, there are many solution techniques presently available to study physical processes in a lake. To cope with all the processes that affect lake circulation in a single model would be a large undertaking which does not appear to have been attempted. In association with mathematical development, field surveys of lake currents, temperature regimes, meteorological conditions and lake topography would be essential. Also important would be the specification of turbulence in the lake for comparison with more recent "turbulence models".

The above discussion is mainly concerned with the problem of analyzing lake circulation. Analysis of mixing goes one step further, because the velocity field has a significant effect on the mixing processes, and must be known before the mixing equations can be solved. Study of mixing has followed a similar path to study of circulation, in that individual mixing processes have been studied separately utilizing simplified equations. Again, field experiments on the mixing of a suitable tracer, usually a fluorescent dye, have been essential to understanding the processes involved. Details of some mixing tests and theories used to explain their results are given, for example, by Kullenberg (1971), Csanady (1963), Murthy (1976), Murthy and Csanady (1971) and Assaf et al (1971). In a recent review of mixing processes in lakes, Ottesen-Hansen (1978) concludes that no reliable analytical description is available to describe turbulent diffusion, therefore field surveys are recommended for practical applications.

The availability and cost of computer programs for mathematical modelling of lake circulation and mixing has not been investigated for the purposes of the present study. Fox et al (1979) have reviewed many lake models including circulation and mixing models. References to a few operational software systems are made in a recent book (Abbott 1979). It appears that most programs have been developed internally by research institutions. A program for calculation of two-dimensional velocity fields described by Harrington et al (1978) is available to the Alberta Research Council and is presently undergoing testing for the problem at hand.

7.2.2 Physical Modelling

The use of hydraulic models for studying circulation and mixing phenomena, although not in an advanced state of development, is a reasonable well-documented technique that has been described in a number of fairly recent papers and reports. In order to illustrate the potential for applying hydraulic modelling to the Athabasca Delta situation, brief notes will be presented on a few of these sources.

Silberman and Stefan (1970) reviewed the state of the art on hydraulic modelling of heat dispersion in large lakes. Although directed towards dispersion of buoyant plumes, this study is partly relevant to consideration of modelling the Athabasca Delta situation. Various theoretical and practical requirements were discussed.

Sobey and Savage (1974) studied jet-forced circulation in reservoirs by means of both physical and mathematical models. A 3-variable non-dimensional diagram was presented for use in preliminary design of reservoirs, relating a circulation parameter to dimensional and hydraulic parameters. In discussion of this paper, Ali and Hedges (1975) presented information on similar experiments and showed a non-dimensional diagram of slightly different form. A later paper by Ali, Hedges and Whittington (1978) described extensive model experiments on circulation induced by inflow and outflow in actual reservoirs, involving investigation of scale effects and of the effects of vertical scale exaggeration. Wind effects were studied separately in the field. Mayer (1975) also reported experiments on both distorted and undistorted reservoir models, designed to study jet penetration and mixing with the aid of dye injections.

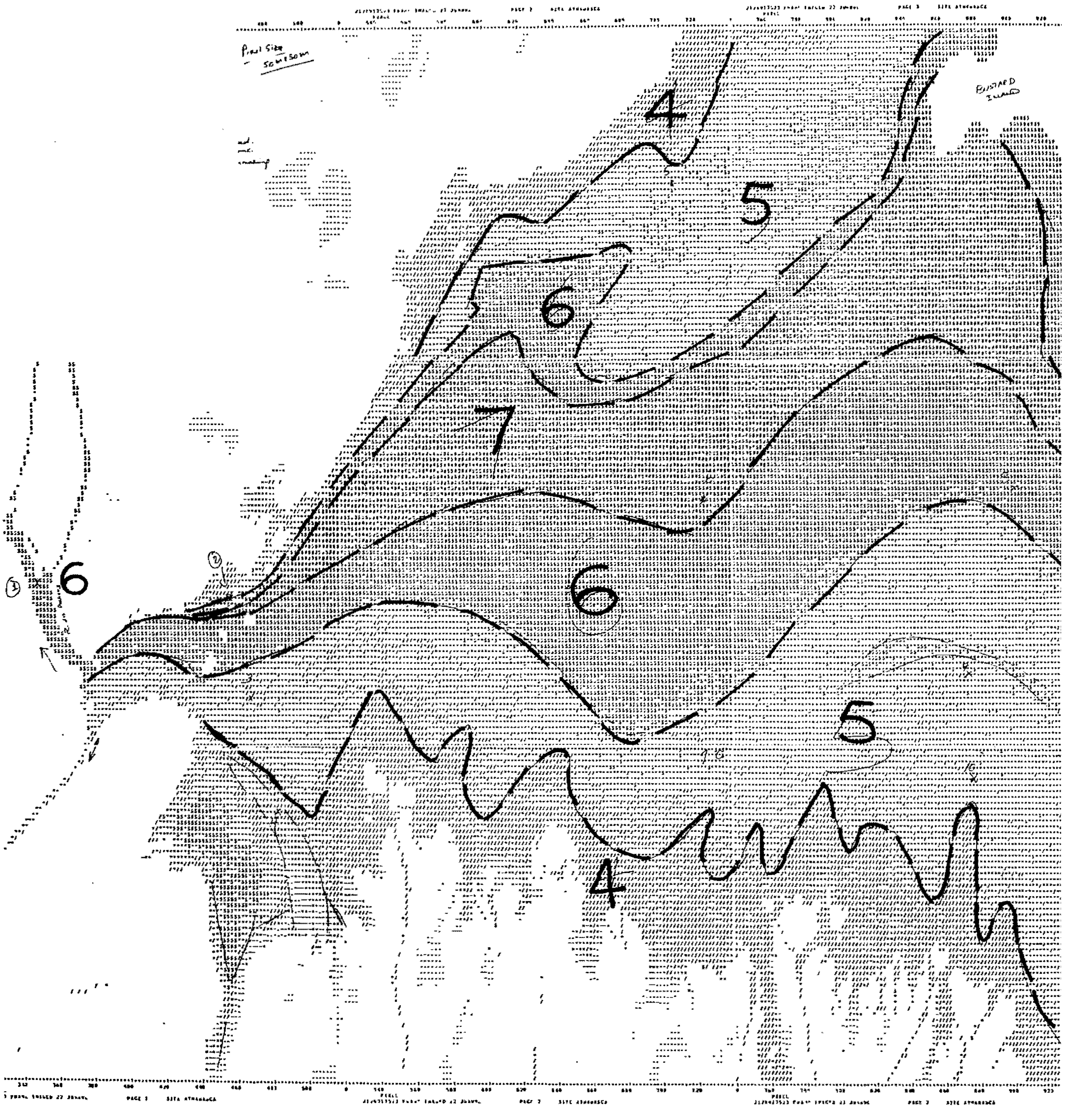
Lean and Weare (1979) used theoretical and numerical experiments to demonstrate some of the difficulties in modeling two-dimensional circulating flow. The implications of their analysis for physical modeling were discussed briefly. They pointed out that vertical distortion is often necessary to ensure turbulent flow, but that there is then a resulting tendency for the model to exaggerate mixing, unless 'shear layer turbulence', produced at an interface between main flow and an eddy resulting from separation, is the dominant source of mixing in both the full-scale situation and the model.

Northwest Hydraulic Consultants Ltd. (1979, 1980) conducted model studies to assist the design of cooling ponds for two thermal power plants in Alberta. In the first case, also reported by Rozeboom (1980), a distorted model was used with representation of inflow, outflow and wind. In the second case both wind and thermal density effects were modelled qualitatively.

7.3 PRELIMINARY DIGITAL ANALYSIS OF SATELLITE DATA

As noted in Section 4.1.2, LANDSAT data are available in the form of computer compatible tapes (CCT) which record digitally the measured reflectance in each band received by the multispectral scanner (MSS). The use of such data for computer mapping of sediment levels in Canada has been demonstrated and discussed by Chagarlamudi and Schubert (1979), Chagarlamudi, Hecky and Schubert (1980), and Munday, Alfoldi and Amos (1979). Basically, the reflectances recorded on the tapes are manipulated into appropriate ranges and the various range bands are shown by different symbols on a computer-plotted map, in a technique similar to optical density slicing. Interpretation in terms of Secchi depth transparency, turbidity, or sediment concentration depends upon sufficient field data being available to calibrate the reflectance ranges.

In view of the lack of field data contemporaneous with satellite data, only a demonstration analysis was procured. Figure 40 shows a computer-plotted map based on Band 5 data from 22 June 1980, comparable with the Band 5 image shown in Figures 16 and 30. If field sediment concentrations for this date had been available, the map could have been interpreted in terms of sediment concentrations. In the absence of such data, it might be unwise to assume that the contoured values of reflectance necessarily correspond to a scale of sediment concentrations.



Zone numbers indicate reflectance in an arbitrary scale ranging from 1 (lowest) to 9 (highest). Generally, higher reflectance indicates higher suspended sediment concentrations.

Figure 40. Digitally-analyzed computer-plotted map based on Band 5 LANDSAT data from 22 June 1980: compare with Figure 16 or 30.

8. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 SUMMARY

The study has accumulated and analyzed a considerable amount of information concerning the flow and sediment system of the Athabasca Delta area, although a complete description of the system under various external conditions cannot at present be achieved. It is important to recall that the present study was viewed as a first-stage study to sketch the essentials of the system and to outline needs and methodologies for better definition.

The main elements of the study were as follows:

1. A general literature review, mainly concerned with lake circulation and mixing, but including brief consideration of the overall hydrology of lakes and of delta hydrology and processes.
2. A summary of previous information on the local hydrology, considering inflows and outflows, lake levels, bathymetry, sediment, ice and wind conditions, and water quality.
3. An analysis and interpretation of satellite imagery covering a selection of the best visibility conditions between 1973 and 1980.
4. A series of three field investigations in September 1979, March 1980 and June 1980, and an analysis of field data on depths, currents, transparency, wind, sediment concentrations, conductivities, and mixing characteristics.
5. Preliminary consideration of the potential for mathematical and physical modelling, and approximate calculations of the zones of influence of inflows and outflows under specific conditions.

8.2 CONCLUSIONS

The following conclusions drawn from the study are grouped under various topics.

8.2.1 Circulation of inflows from Athabasca River in Lake Athabasca

LANDSAT images indicate that during normal open water conditions in later summer and fall, Athabasca River inflows tend to short-circuit to the lake outlet near Fort Chipewyan and affect only a narrow band of Lake Athabasca adjacent to the delta. At its widest point opposite the mouth of Big Point Channel, this band is normally about 8 km wide.

Under less frequent conditions of high inflow from the Athabasca River, it appears that river water may extend north as far as Bustard Island, approximately 15 km from the delta shoreline. Such conditions probably pertained in the spring flood conditions of May 1974 when the whole delta complex was flooded, in early July 1975 following a flood inflow, and in June 1980 following the flood inflow that coincided with the field program. In more usual conditions the relatively steady lake throughflow current from northeast to southwest, resulting from inflows from the Canadian Shield, acts to confine the Athabasca River inflows to the narrow zone previously described.

Under winter ice conditions, penetration by river water appears to be similar to that under fall or open-water conditions. Most of the lake outflow is derived from lake throughflow, and movement of river water off the delta front is barely perceptible. There is no definite evidence as to whether river water tends eastward under the influence of the earth's rotation, as might be expected on theoretical grounds.

There is a large difference between proportions of river and lake water in the outlet channels at different times of year. In spring and early summer, outflows are 80% to 90% river water, whereas in winter they are mainly lake water.

Wind appears to have an important effect on the shape of the zone occupied by river water and on the direction of the inflow currents in the lake. This is not surprising, because wind-induced currents can be expected to be comparable in magnitude with inflow currents under conditions that occur fairly frequently.

8.2.2 Mixing of River and Lake Waters

In LANDSAT images the degree of mixing at the boundary between river and lake waters can be assessed qualitatively by the fuzziness of the boundary between different tonal or color zones. Generally, image patterns suggest relatively little mixing in late summer and fall, but more mixing under high inflow conditions when inflows extend north into greater depths. A similar picture emerges from examination of specific conductance data: relatively abrupt changes are present under low inflow conditions, but more complex gradients and alternations are seen under high inflow conditions, as in June 1980.

At the main lake outlet, satellite and aerial photographic pictures frequently indicate two or more distinct surface streams entering Riviere des Rochers. Direct evidence of this is provided by conductance data from June 1980, which indicated a central surface stream of lower conductance. Under-ice conductance data from March 1980 showed a marked vertical profile, the more conductive and presumably denser river water occupying the bottom of the cross-section, and the surface layer apparently consisting of unadulterated lake water. Only a weak vertical gradient was apparent in June 1980, but stronger vertical gradients probably exist under more steady conditions. Since it seems unlikely that a strong vertical stratification could exist in the shallow water of the lake itself, the vertical stratification in the deep outlet channel probably results from rotation of a pre-existing horizontal stratification.

Satellite images and aerial photography suggest that mixing of outflow streams generally takes place in the first 3 km or so of Riviere des Rochers. Field investigation in June 1980 found a fully mixed condition at a point about 20 km downstream.

The proportion of Athabasca River water in Riviere des Rochers varies from over 90% in high inflow periods to less than 10% in winter. On the basis of annual water balance, it should average about 53%. The average of 7 daily determinations at different times of year, listed in Table 12, is 57%. These proportions can be determined by analysis of conductance data at the lake outlet, and are approximately confirmed by analysis of lake current data in the area southwest of Bustard Island.

Results of dye injection at a point out in the lake, about 10 km southwest of Bustard Island, showed that dispersion of surface layers in the lake was strongly affected by wind, the dispersion coefficient in the wind direction being approximately 20 times greater than in the transverse direction. In view of this result, some of the preceding comments on the influence of inflow conditions on mixing may require qualification with respect to wind conditions.

There are essentially no vertical temperature gradients in the shallow southwest portion of Lake Athabasca, so that the lake water is essentially homogeneous with respect to depth.

8.2.3 Interflows Between Lake Athabasca and Mamawi Lake

Lake interflows were not specially investigated as part of the present study, but a brief analysis of Alberta Environment measurements has been conducted as part of the Slave River Project environmental studies. Data are rather limited, but suggest that under open water conditions in 1977, water flowed west into Mamawi Lake at least as often as it flows east out of Mamawi Lake, which is contrary to what would be expected from water balance considerations. It must be noted, however, that westward flow is often caused by wind set-up at the outlet of Lake Athabasca, a phenomenon that would apply mainly during the daylight hours when measurements were made.

8.2.4 Sediment Balances

Analyses of limited sediment data for 1973, 1975 and 1976 indicated that, on average, about 65% of the sediment inflow from the Athabasca River passes through to the Slave River via Riviere des Rochers. The portion passing through consists mainly of fine to medium silt plus clay, coarse silt and sand being deposited in the Athabasca Delta channels or at the delta front in Lake Athabasca. During a 10-day flood period in June 1980, sediment outflow was only about 40% of inflow, but it can be expected that over a longer period more sediment would be released from temporary storage in the lake.

Volumetric considerations indicate that if the above estimates are correct, the delta front should be advancing areally by about 0.8 km^2 per year. Comparison of recent satellite images with aerial photography from the nineteen-fifties appears to confirm this figure, which is several times greater than the apparent average over the post-glacial geological period: the reason for this apparently substantial increase in recent times is not definitely known. The delta front is composed of silt and fine sand and has a very flat slope.

It appears that a small proportion of sediment outflow from Lake Athabasca originates from sources other than the Athabasca River. The sources of this sediment in the 'lake' water have not yet been determined. Although sediment from these other sources is probably a very small part of the annual outflow tonnage, its presence is indicated by certain pictures from late summer and fall when the Athabasca River is low in sediment.

It has not been possible to determine sediment exchanges between Lake Athabasca and Mamawi Lake, nor sediment inflow during backflows from the Peace River. These exchanges are probably of little significance in the overall sediment balance. Approximate estimates could be made if required from considerations of flows and sediment contents.

8.2.5 Investigative Techniques

It was hoped that the field programs would permit a definite comparison between remote sensing data and field data. Unfortunately this has not been feasible because of weather conditions in September 1979 and an unforeseen shut-down of satellite sensors during the critical period in June 1980. A crucial question therefore remains unanswered: whether in this environment there is a monotonic relationship between LANDSAT image brightness and sediment content of the water, as has generally been reported elsewhere, or whether there is an anomaly resulting from other factors that distinguish Athabasca River water from Lake Athabasca water, as appears to be suggested by some of the LANDSAT data.

With regard to LANDSAT images, Band 5 and Band 6 black-and-white and Band 4/5/7 color composites have all been found useful in interpretation of circulation, mixing and sediment patterns. Band 5, generally recommended for sediment studies, appears most useful at lower concentrations and Band 6 (which gives a near-surface picture) at higher concentrations.

River and lake water can be easily distinguished by various water quality properties, of which specific conductance is the most convenient.

At least for lower sediment concentrations (up to 100 mg/L), there is a good correlation with the optical property of turbidity. Comparisons at higher concentrations were overlooked. In the highly turbid conditions that usually apply, Secchi depth readings are of little value for discrimination.

The usefulness of digitally-analyzed computer-plotted LANDSAT data has been demonstrated. In any further studies, more use should be made of this technique to quantify reflectance patterns.

8.2.6 Modelling

It is evident that if detailed predictions are to be made of circulation and distribution over a specified range or sequence of governing hydrologic and climatic conditions, some form of modelling will be necessary to provide a framework for proper utilization of the available field observations. This is particularly true if predictions are required for an unnatural combination of conditions that might result from a dam on the Slave River or other developments.

It has been shown that tools are available to construct a mathematical circulation model to various levels of sophistication, but that it would be difficult to provide for the full range of possibly significant phenomena in a single model. Consideration of mixing and of sedimentation raises further complexities which have been only briefly considered. An appropriate next stage would be to procure and test available computer programs that can be used to construct a circulation model of this particular system. The possibility exists, given a definition of velocities in Lake Athabasca, of postulating a sequence of inflows to the lake with associated sediment concentrations in the Athabasca River, and predicting on a more or less continuous basis the deposition of sediment in the delta front and the transport of sediment through the various outlet channels. Such a model could be used to determine the effects of changed hydraulic conditions downstream as a result of proposed Slave River hydro developments.

The necessity for an adequate amount of field data to calibrate and verify a mathematical model cannot be over-emphasized. In some cases, if sufficient data are available to calibrate a circulation and diffusion model, the model is scarcely required to solve the problem at hand.

For rapid insight into the effects of postulated conditions or changes, a physical hydraulic model might be of some value. A combination of mathematical and physical modelling might be ideal. Physical modelling could be useful for studying the effects of ice cover and wind.

8.2.7 Implications with Regard to Contamination of the Athabasca River

The following tentative inferences can be drawn with regard to contaminants (i) on the water surface or distributed through the water, (ii) attached to suspended sediment, and (iii) associated with bed transport.

Surface or distributed contaminants not attached to sediment can be expected to circulate in the part of Lake Athabasca within about 10 km of the delta shoreline and to pass through to the Slave River with reduced concentrations but little loss of mass. In conditions of strong northeast winds, however, and possibly in other conditions, some contaminated flow could pass into Mamawi Lake. In conditions of high river inflow or strong southwest winds, contaminants might reach Bustard Island or beyond.

Contaminants attached to suspended sediments would be partly retained in the delta and in Lake Athabasca, the rest passing through to the Slave River with minor loss to Mamawi Lake. The proportion retained would depend importantly on the sediment size range involved.

Contaminants associated with river bed transport would be retained in the delta and on the bed of the immediate offshore area within about 5 km of the delta shoreline.

8.3 RECOMMENDATIONS FOR FURTHER STUDIES

The following suggestions are offered for further work in extension of the studies described in this report.

8.3.1 Remote Sensing and Field Studies

Further efforts should be made to obtain field data contemporaneous with LANDSAT overpasses. Given good visibility, data collected should include suspended sediment concentrations, turbidity and specific conductance. These can be collected by boat or floatplane, with electronic position-fixing as in June 1980.

A library of all useable satellite imagery could be assembled, and appropriate environmental data assembled for each useable date, to extend the interpretation studies described herein. Images of the northeast part of Lake Athabasca should also be examined to investigate the sources of turbidity in the lake water.

To permit further investigation of the role of seiches in lake circulation, collection and analysis of water level data should be combined for the recording stations at Fort Chipewyan, Bustard Island and Crackingstone Point. Consideration should be given to acquiring reliable data on winds on the lake.

Monitoring of water quality should be continued throughout the year at Big Point Channel, at Sand Point in Lake Athabasca, and in Riviere des Rochers near Revillon Coupe, in order to enable calculation of river and lake water proportions in the lake outflows.

Further dye and drogue experiments might be performed to obtain further information on times of travel of inflow water in various conditions including under ice cover.

8.3.2 Modelling

Further work could be done to procure and test appropriate computer programs for construction of a mathematical model of the circulation and mixing system.

The question of modelling sedimentation processes in the delta and in Lake Athabasca has barely been considered in the present study.

Further consideration could be given to the scaling and design of a physical model of the system. As an initial objective for modelling, it might be appropriate to specify prediction of the water and sediment conditions corresponding to mean environmental conditions (inflow, outflow, lake level, wind, etc.) for each month of the year both under present controls and under proposed alterations due to a Slave River dam.

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10. LIST OF AOSERP WIDE DISTRIBUTION RESEARCH REPORTS

Report	Project	Reference
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2	AF 4.1.1	Kristensen, J., B.S. Ott, and A.D. Sekerak. 1976. Walleye and goldeye fisheries investigations in the Peace-Athabasca Delta--1975. Prep. for the Alberta Oil Sands Environmental Research Program by LGL Ltd., Environmental Research Associates. AOSERP Report 2. 103 pp.
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