Hydro Québec
Production

Environmental Monitoring of the La Grande-2-A and La Grande-1 Projects

Abridged Summary Report 1987-2000

La Grande Rivière Winter Plume

APRIL 2005

Environmental Monitoring of the La Grande-2-A and La Grande-1 Projects

ABRIDGED SUMMARY REPORT 1987-2000

LA GRANDE RIVIÈRE WINTER PLUME

HYDRO-QUÉBEC

DIRECTION BARRAGES ET ENVIRONNEMENT

and

GENIVAR GROUPE CONSEIL INC.

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1. Introduction

The La Grande complex hydroelectric developments (Figure 1) were built in two phases. Phase I of the La Grande complex got under way in 1973 and was completed in 1985. It includes three generating stations: Robert-Bourassa[1], La Grande-3 and La Grande-4. Each of them has its own reservoir, in addition to Caniapiscau and Opinaca reservoirs formed by two partial river diversions. As a result of these diversions, the mean annual flow of the La Grande Rivière at its mouth doubled from about 1,700 m^3/s to 3,400 m^3/s.

The construction program for Phase II of the La Grande complex called for five more generating stations to be built: La Grande-1, La Grande-2-A, Laforge-1, Laforge-2 and Brisay. Only two new reservoirs were required, La Grande 1 and Laforge 1; the other generating stations use Phase I reservoirs.

SEBJ (Société d'énergie de la Baie James or James Bay Energy Corporation) was given a mandate to implement an environmental monitoring network (EMN) at the La Grande complex. At the outset, the EMN's core activities dealt with water quality, phytoplankton, zooplankton, benthic macroinvertebrates and fish communities, along with mercury in fish, as a complementary activity. The EMN was optimized in 1987, and thereafter, measurements in aquatic environments were limited to water quality, fish communities and mercury in the flesh of fish.

In addition, monitoring programs focused on the main terrestrial and avian wildlife resources, their habitats, as well as components of the social environment (archeology, land use, etc.) Studies were also conducted on the estuaries of rivers modified by the hydroelectric developments and along the northeast coast of James Bay, because of its geographic location and the diversity of its habitats, of vital importance to several species of migratory birds, particularly waterfowl.

After commissioning of the La Grande complex phase I, the mean winter flow of the La Grande Rivière varied between 3,500 m^3/s and 4,000 m^3/s. In winter, it forms a freshwater plume over the salt waters of James Bay, which are covered by landfast ice extending 15 km to 20 km seaward followed by open waters and drifting ice. Under such conditions, the plume extends 2,000 km^2 and is 5 m to 6 m thick.

Following the addition of the La Grande-2-A generating station, monthly mean flows of La Grande Rivière reach 4,000 m^3/s in November and December and more than 4,500 m^3/s in January and February. La Grande-1 is a run-of-river generating station synchronized with Robert-Bourassa and La Grande-2-A stations.

1 By resolution of the Québec Cabinet, La Grande 2 reservoir, along with its generating station and dam, were renamed Robert-Bourassa in October 1996.

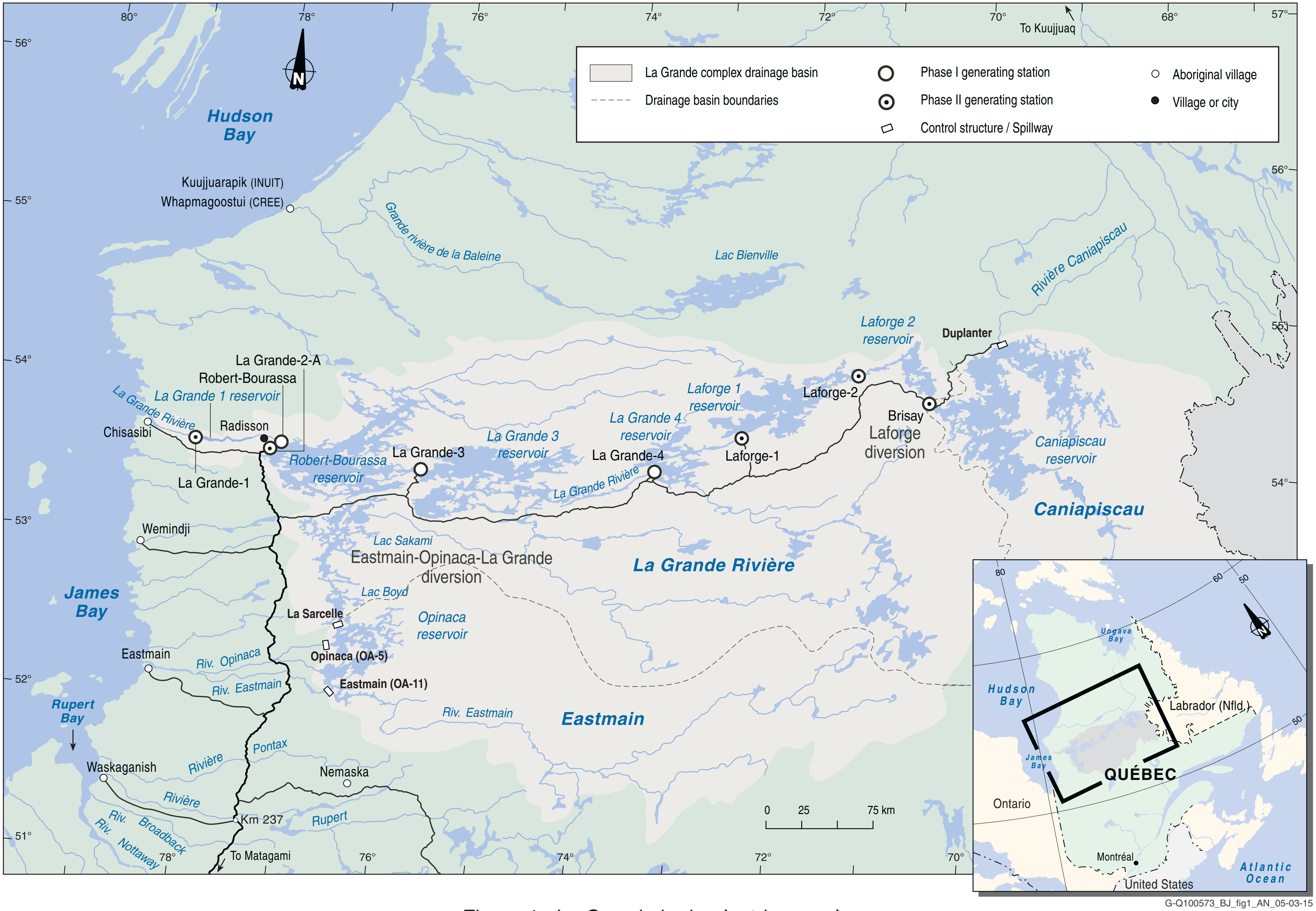

Figure 1 La Grande hydroelectric complex

Monitoring of the physical characteristics of the northeast coast of James Bay was limited to the monitoring of the freshwater plume of the La Grande Rivière in winter, because it is the winter flows that are the most modified by the addition of the La Grande-2-A generating station.

Monitoring objectives were:

- To measure the thickness of the plume and the spatial variations of the salinity under ice;
- To measure the order of magnitude of these variations within the plume's total area;
- To verify the hypothesis of increased mixing of the fresh and salt waters with increasing flows from the La Grande Rivière; and
- To measure the role of the plume in the seston (fine particulate matter) transport along the northeast coast of James Bay.

Recently, Hydro-Québec has produced French versions of several summary reports for each of the EMN's components: hydrological and ice regimes of the La Grande Rivière, shore dynamics of the La Grande Rivière, riparian vegetation of the La Grande complex, evolution of fish mercury levels, changes in fish communities, the winter plume of the La Grande Rivière and eelgrass along the northeast coast of James Bay.

Complete or abridged English versions of several of these summary reports were produced to inform the Cree communities on changes that took place in the James Bay territory.

This document is an English abridged version of the summary report (1987-2000) produced by Messier (2002) on the monitoring of the La Grande Rivière's winter plume.

2. Impact prediction

This chapter briefly reviews the potential impacts of the La Grande hydroelectric complex on the winter freshwater plume of the La Grande Rivière, as assessed prior to the construction of the La Grande-2-A and La Grande-1 generating stations.

From studies conducted between 1974 and 1984, it is known that the freshwater plume of the La Grande Rivière comprises three zones: (i) the proximal zone (heart of the plume), made up of a freshwater layer (salinity ≤ 5‰) overlying a salt water layer (salinity ≥ 20‰) separated by a definite pycnocline, where the water density gradient is maximal; (ii) a frontal zone where surface salinity increases rapidly over a short distance and (iii) a distal zone, adjacent to the previous zone.

Because the existing models were inadequate to correctly predict the extent of the freshwater plume after commissioning of the La Grande-2-A generating station, SEBJ developed its own empirical model to do so. Table 1 provides modeling results (plume length and area) for La Grande Rivière flows varying from 3,000 m^3/s to 5,500 m^3/s after commissioning of La Grande-2-A generating station.

Table 1 Predicted length and surface of the La Grande Rivière winter plume for flows varying from 3,000 to 5,500 m^3/s

La Grande Rivière discharge (m^3/s)		Limit of the frontal zone of the plume (isohaline of 10‰)	Total limit of the plume (isohaline of 20‰)
3,000	Length[1] (km)	45	55
	Area (km^2)	1,080	1,650
4,300	Length (km)	56	75
	Area (km^2)	1,680	3,000
5,500	Length (km)	62	90
	Area (km^2)	2,046	4,410

1 Position of the frontal zone is distributed 75% north of the La Grande Rivière and 25% south according to the proportion of the outcoming flows of its two main channels.

3. Methods

Two approaches were used to measure the extent of the winter plume of the La Grande Rivière:

- Salinity and temperature profiles at several stations; and
- Installation of current meters in strategic locations which register (continuously for a defined period of time) water temperature and salinity as well as current speed and direction.

The 1987 and 1989 winter campaigns served to better assess baseline conditions. The 1993 and 1995 winter campaigns were aimed at measuring the La Grande Rivière's winter plume after commissioning of the La Grande-2-A generating station.

Table 2 provides a summary of the field work and various parameters measured from 1989 to 1995.

Table 2 Summary of field work for the monitoring of the winter plume of the La Grande Rivière

Component	1987	1989	1993	1995
Salinity - Temperature profiles				
Measurement period	Feb. 20 to March 1st	Feb. 20 to March 4	Feb. 14 to 23	Feb. 7 to 26
Characteristic flow[1] of the La Grande Rivière (m^3/s)	3,700 m^3/s (Feb. 1st to March 1st)	4,000 m^3/s (Feb. 15 to March 4)	4,600 m^3/s (Feb. 9 to 23)	4,400 m^3/s (Feb. 7 to 26)
Station positioning technique	Mini Ranger III	Loran C	GPS	GPS
Area covered (north to south)	Roggan River to Dead Duck Bay	Tees Bay to Comb Islands	Roggan River to Dead Duck Bay	Roggan River to Au Castor River
Measuring instrument	Salinity – Temperature – Depth probe every year			
Number of stations	83	38	92	156
Number of profiles[2]	85	168	101	156
Depth	From surface to bottom or at a maximum of 25 m			
Current				
Measurement period	Feb. 23 to April 12	Feb. 17 to April 25	Feb. 18 to April 24	Feb. 18 to April 11
Type (and number of current meter used)	Aanderaa (5)	Aanderaa (9)	Aanderaa (2)	Aanderaa (2)
Parameters measured	Temperature, Conductivity, Salinity, Current speed and direction			
Water chemistry[3]				
Period	Feb. 23 to April 12 1987			
Area and stations sampled (north to south)	34 stations between Roggan River and Dead Duck Bay			
Sampling	In surface layer (0.5 to 3 m) along a salinity gradient. 14 samples from the bottom layer (5.5 to 20 m)			
Parameters measured	• Chlorophyll *a* and pheopigments • Particulate organic nitrogen and carbon • Nitrates, silicates and orthophosphates • Suspended particulate matter • Size of particulate matter at 9 stations			
Analytical methods	• Standardized methods for fresh and salt waters			

1 The characteristic flow is an approximation of the mean flow of the La Grande Rivière during the measurement period, including 5 days before.
2 Several profiles were measured at a same station.
3 Water chemistry of the plume was only measured in 1987.

4. Results

4.1 Baseline conditions

The research program, in both 1987 and 1989, investigated the « freshwater – saltwater » mixing processes on the coastal shelf and the winter freshwater plume dynamics.

Distribution of the surface isohalines

The core of the freshwater plume, delineated by the 5‰ surface isohaline, extends over 65 km, from the Bay Of Many Islands north of the La Grande Rivière to Dead Duck Bay in the south (Figure 2).

Taking into account the influence of Roggan River and Au Castor River, the overall freshwater plume (as defined by the 20‰ surface isohaline), extends from Point Attikuan, 50 km north of the La Grande Rivière, to the Brea Islands located 45 km south of the La Grande Rivière. Excluding the input of the Au Castor River, the southern boundary of the freshwater plume would reach the Comb Islands, 5 km further south.

Whether under 3,700 m^3/s flow conditions (1987) or 4,000 m^3/s flow conditions (1989), the plume, recorded over 95 km along the coast and up to about 20 km offshore, covers some 2,000 km^2, of which 1,200 km^2 are considered within the core of the plume, which is approximately 20 km wide.

Vertical structure of the plume

From Goose Bay to Dead Duck Bay, the underice plume comprises two layers: a surface layer where salinity is less than 5‰ overlying a second layer where salinity reaches 22‰ (Figure 3). The pycnocline (layer of maximum density gradient) is located at a depth between 4 m and 6 m. The salinity goes from 2 to 22‰ over only about 2 m in the water column. The position of the pycnocline varies significantly during a day in relation with the tidal state (Messier et al., 1989). Shortly after high tide, the pycnocline rises to the surface, increasing mixing and salinity in the surface layer, while at low tide, the opposite occurs.

Near the « *landfast ice – open water* » border, located less than 10 km offshore, the isohalines rise toward the surface, and the salinity profiles are stair shaped. The open water seems to limit the offshore extent of the plume. The majority of the salinity profiles recorded off the fast ice prior to 1987 showed that the two-layer salinity structure did not occur then (Freeman and Flemming, 1982; Larouche, 1984).

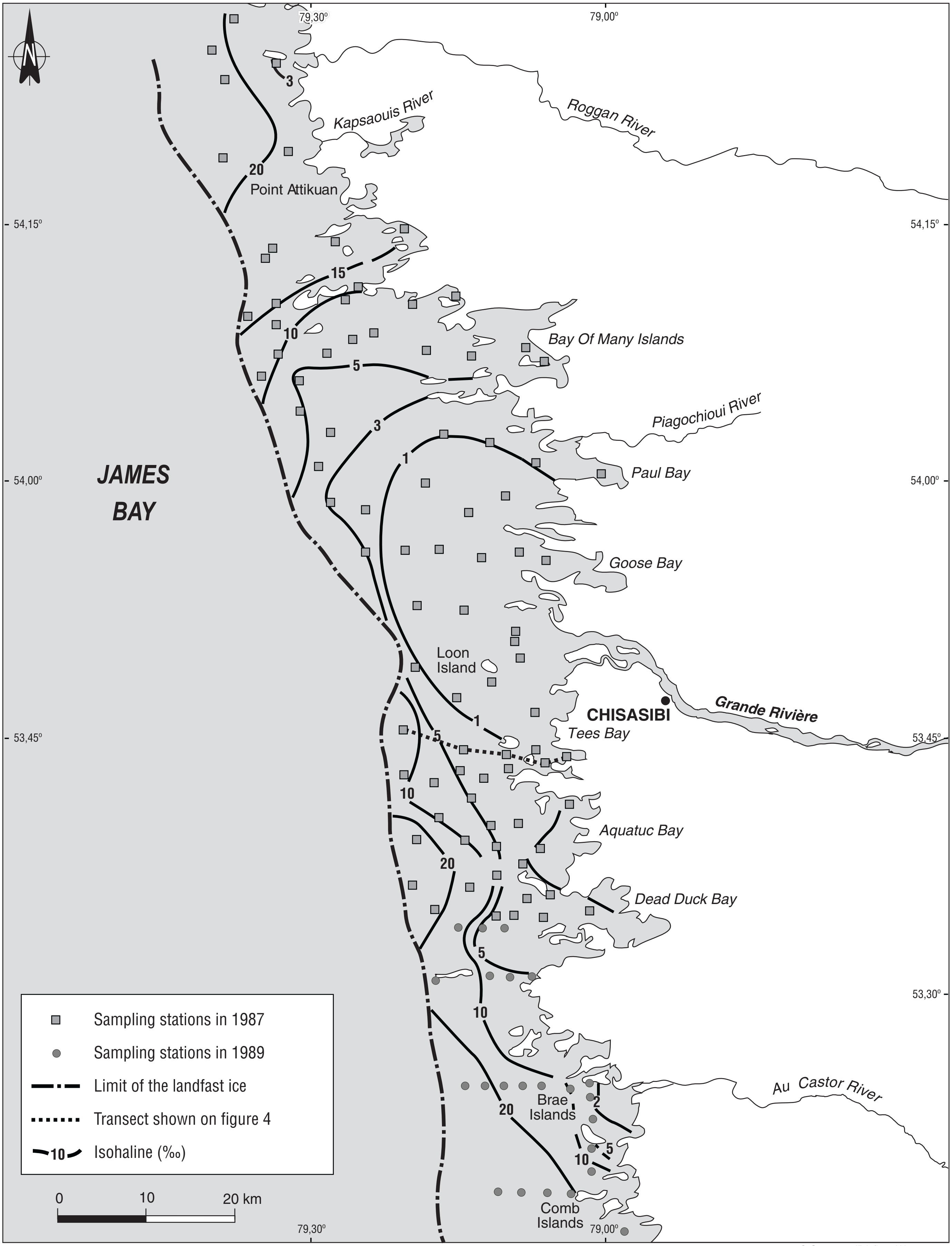

Figure 2 The Grande Rivière winter plume surface isohalines, from 1987 and 1989 data.

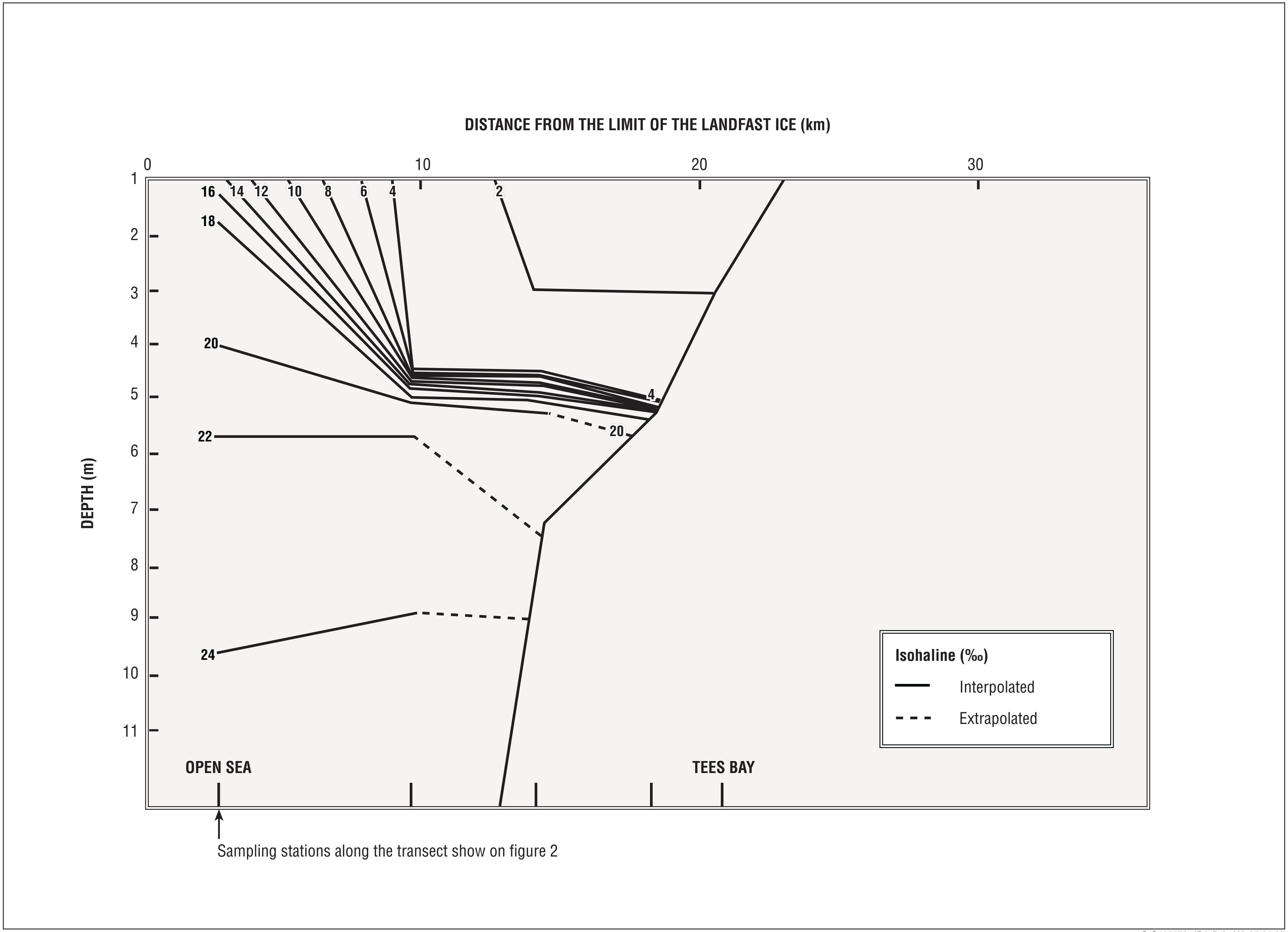

Figure 3 Cross section structure of the winter plume of the La Grande Rivière in 1987.

Exchanges between the coastal bays and the coastal platform

The profiles recorded in the coastal bays during the winter of 1987 indicate that the salinity structure is similar to that on the coastal platform. It is also the case for unregulated rivers when the freshwater input is the lowest. In March and April, salinity increases both at the surface and in deeper layers.

Current measurements in the Bay Of Many Islands and in Dead Duck Bay, in the winter of 1987, reveal that current variations are related to the tide and that salinity variations are caused by events of longer periods than the tide.

Variability of the extent of the plume

The extent of the La Grande Rivière plume presents variations through time, in the location of the 5‰ and 20‰ isohalines in relation to the coast.

In 1989, south of the La Grande Rivière, the 20‰ isohaline was found between 12 km and 20 km offshore in the maximum range conditions, and between 7 km and 12 km in the minimum range conditions (Figure 4). The 5‰ isohaline was recorded between 5 km and 12 km offshore in the maximum range conditions, and between 2 km and 8 km in the minimum range conditions. When applied to the overall plume (northern and southern areas), this translates into 700 km^2 variations of the surface area of the total plume (20‰ isohaline), and into 200 km^2 variations for the core of the plume (5‰ isohaline).

These variations of the plume range could not be related to the tide; the bi-monthly variations related to the tide seemed to be masked by the local water circulation related to the complex topography and shallow waters of the bays. Also, the La Grande Rivière discharge remained stable from February 16 to March 12,1989 with an average of 4,071 ± 113 m^3/s. Therefore, factors other than the tide or the La Grande Rivière discharge regulate the extent of the winter plume.

Relation between the extent of the plume and the discharge of the La Grande Rivière

Despite discharge increases of 1,000 m^3/s and 2,000 m^3/s, the northern limit of the plume core remained at 30 km from the river mouth, while the southern limit progressed by 10 km in 1987 and by 20 km in 1989, inducing an increase of 400 km^2 of the plume core surface area (Table 3).

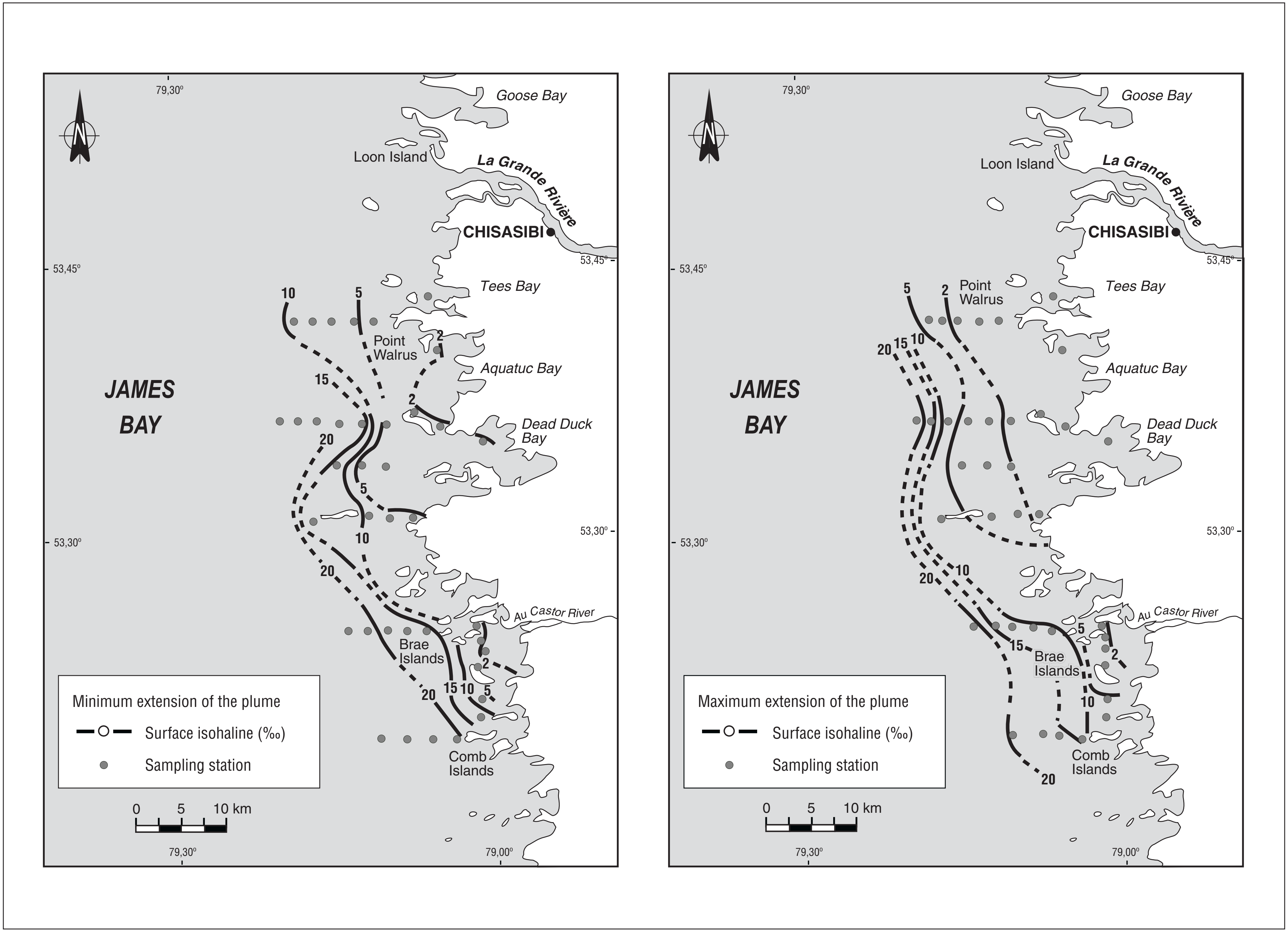

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Figure 4 Maximum and minimum extent of the La Grande Rivière winter plume in March 1989.

Table 3 Linear expansion of the winter plume from the mouth of the La Grande Rivière, from 1980 to 1989.

Year	La Grande Rivière discharge (m^3/s)	Distance under 5‰ (km)		Distance under 10‰ (km)		Distance under 20‰ (km)	
		North	South	North	South	North	South
1980	1,700	30	15	30	-	40	-
1984	2,600	30	15	45	15	?	-
1987	3,700	30	25	40	-	50	-
1989	4,000	-	35	-	40	-	45

For the total plume, the expansion to the north is in the order of 10 km, but the expansion in the south is unknown, as only the 1989 isohalines can be closed to the shore. If the same expansion is applied to the south, the surface area of the plume would have increased by 400 km^2.

Physicochemical characteristics

The deep saltwater of James Bay contains less sestonic elements than the lower salinity surface water. The concentrations in sestonic elements, although globally higher in the surface waters than in the deep waters, do not vary with distance or salinity. They are more influenced by local conditions induced by fronts or recirculation (SEBJ, 1990). Their concentrations in the coastal waters of James Bay in winter are similar to those measured in the coastal waters of south-eastern Hudson Bay (Legendre et al., 1981).

In conclusion, the inputs of the La Grande Rivière in sestonic elements and nutrients to the coastal waters of James Bay are not significant in winter. Neither are they in the summer, as the James Bay waters remain low in nutrients (Roche, 1983a).

4.2 Evolution of the winter plume (1993 and 1995)

The 1993 and 1995 February field surveys were conducted when the La Grande Rivière discharges were 4,600 m^3/s and 4,400 m^3/s respectively.

The data from salinity and temperature profiles from additional surveys conducted in April of 1993 and 1995 (CSSA, 1993a,b; 1995b) were also used to investigate the mixing mechanisms, especially the role of open water zones west of the landfast ice as a control factor of the plume extent under the ice.

Distribution of surface isohalines

As in 1989, the extent of the La Grande Rivière plume in February 1993 and 1995, shows variations in time. In 1993, the total surface area of the plume (20‰ isohaline) varies from 3,200 km^2 to 3,500 km^2, according to the minimum or maximum expansion of the plume (Figure 5). The surface area of the plume core (5‰ isohaline) covers 1,637 km^2. In 1995, the total surface area of the plume varied from 2,100 km^2 to 2,800 km^2, while the plume core ranged from 1,350 km^2 to 1,600 km^2 (Figure 6).

Figure 7, which presents the profiles at four stations at different days in February 1993, clearly reveals the variability of salinity with time (1 day and 7 days), especially for surface waters. The deviations measured range from 5‰ to more than 10‰.

The northern sector is also influenced by the freshwater input of the Kapsaouis River and the Roggan River. The influence of the Roggan River on coastal salinity had already been noted in 1987. It is very likely that the La Grande Rivière plume mixes with the plumes of other tributaries of James Bay which contribute to reduce the salinity over a coastal band of about 10 km.

Vertical structure of the plume

In February 1993, at the level of Dead Duck Bay, the frontal limit of the plume south of the La Grande Rivière is located at the edge of the landfast ice. The isohalines are vertical and salinity goes from 10‰ to 20‰ in 2 km. In that area, the plume is about 5 m thick. In 1995, the survey south of Dead Duck Bay showed that the frontal limit of the plume is closer to the coast and is found under the landfast ice.

In the core of the plume, at the mouth of the La Grande Rivière (between Point Wastikun and Grey Goose Island), the plume (20‰ isohaline) extends to some 25 km west of the landfast ice in 1993 (Figure 5) and to 15 km in 1995 (Figure 6).

The 1993 and 1995 plumes become more different at Point Kakassituq in the north. In 1993, the surface waters with a salinity below 10‰ are found under the ice cover, while the 20‰ isohaline extends far to the west, at more than 30 km from the landfast ice. The pycnocline is not well defined in that area. In 1995, the 20‰ isohaline exceeds the limit of the landfast ice by less than 5 km, while the surface salinity under the ice is higher than 15‰. The plume is almost at its northern limit.

Salinity in the coastal bays

The surface water salinities (depth of 2 m or less) in five coastal bays and offshore from these bays in February 1995 are summarized in Table 4. Paul Bay and Tees

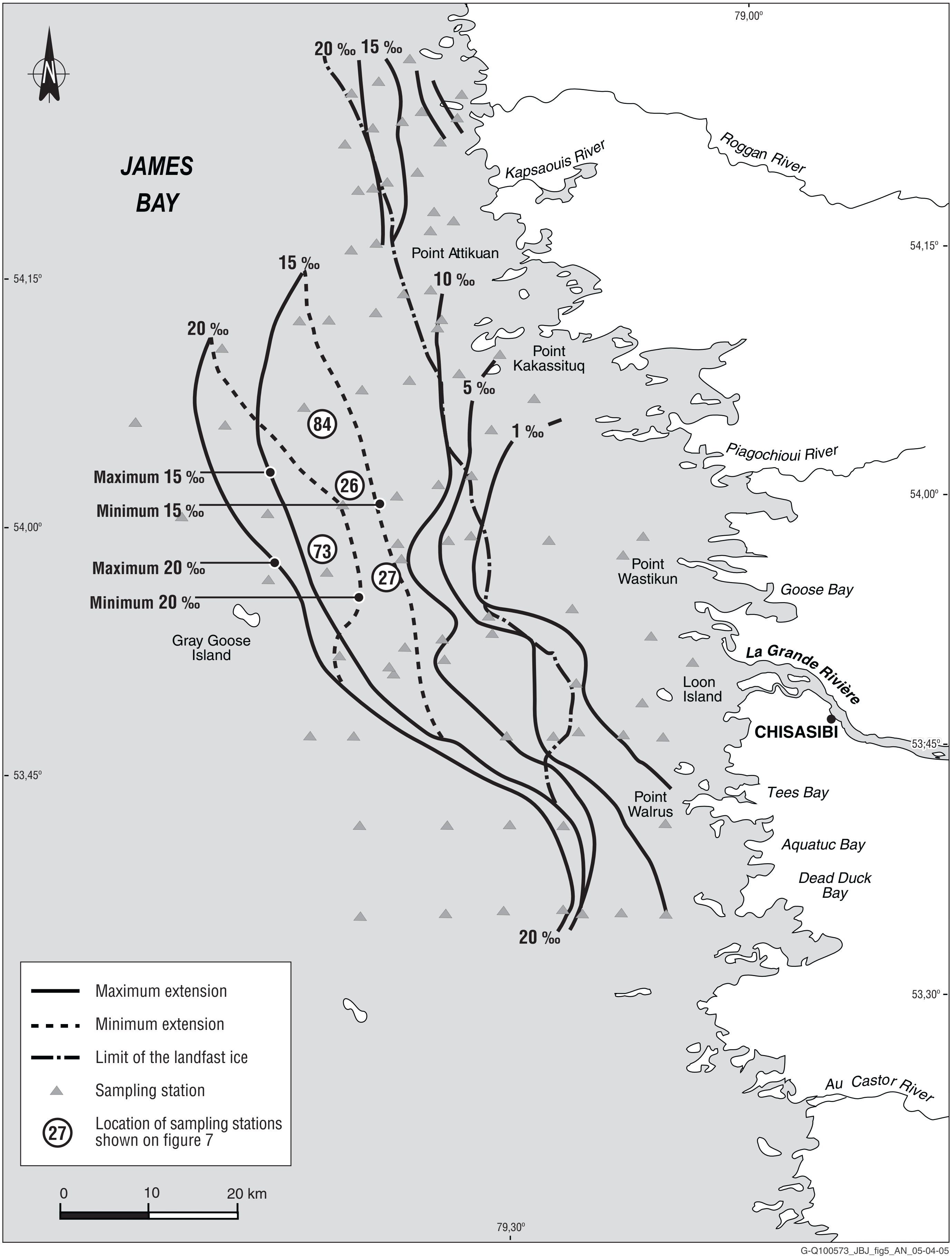

Figure 5 The La Grande Rivière plume under the ice in February 1993.

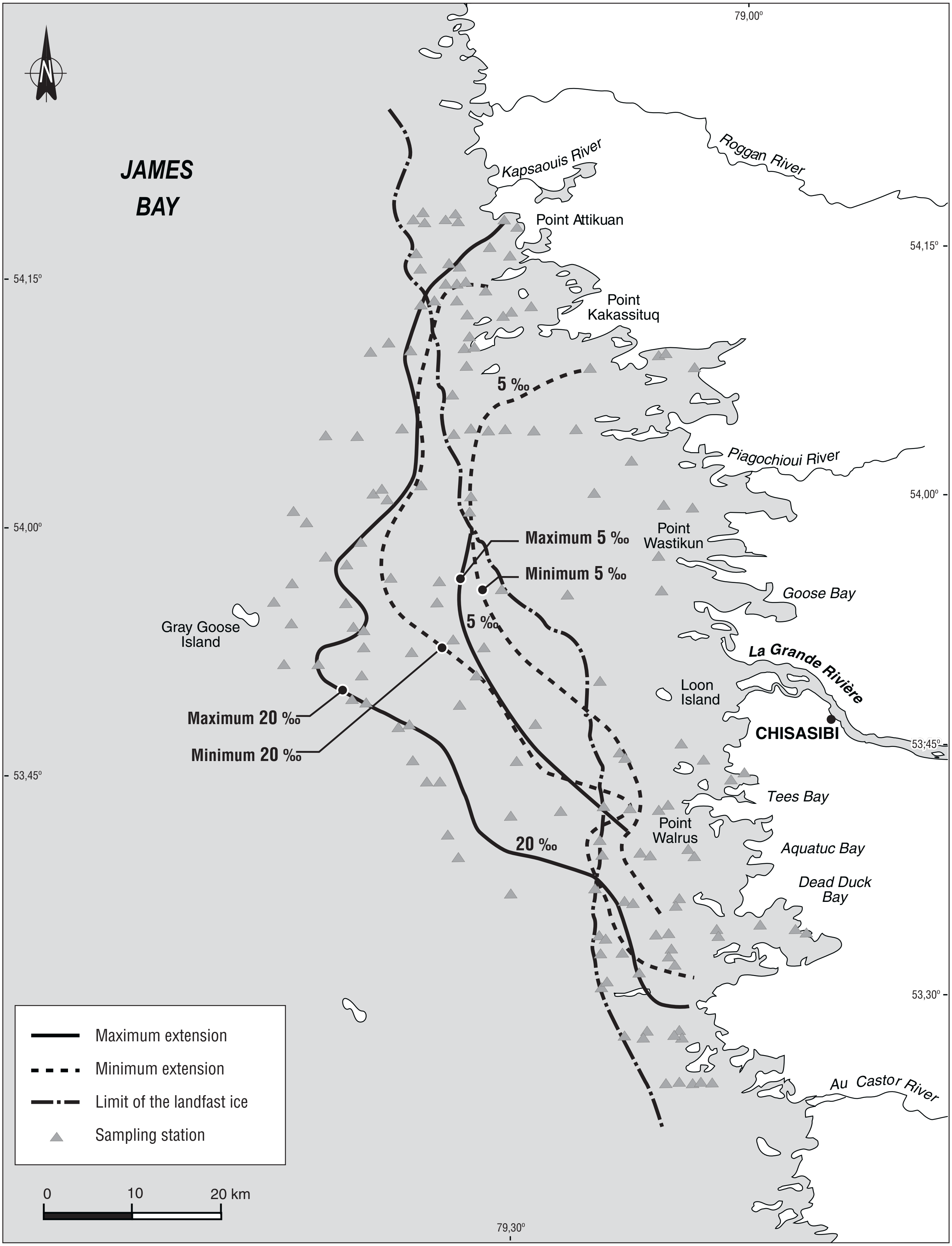

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Figure 6 La Grande Rivière plume under the ice in February 1995.

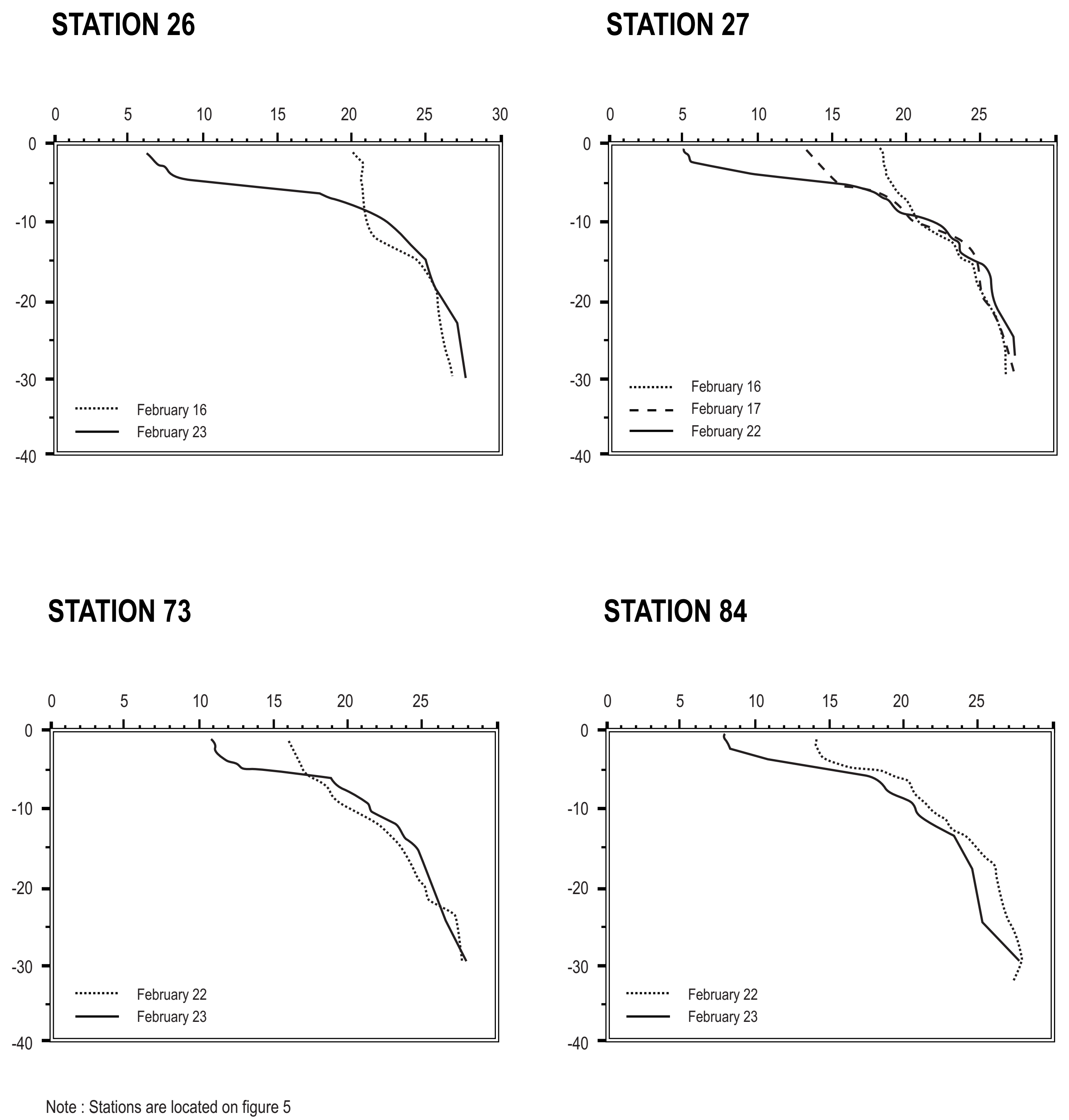

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Figure 7 Salinity profiles at four stations sampled in February 1993.

Bay, located in the plume core, north and south of the mouth of the La Grande Rivière, have a surface salinity of 1‰ or less in February. In the other bays, located outside or at the limit of the plume core (5‰ isohaline), salinity is much higher and varies from 5‰ to 23‰.

Table 4 Surface water salinity in five coastal bays and offshore from these bays in February 1995

Date	Bay	Offshore from the bays	At the shore end of the bays
North of the mouth of the La Grande Rivière			
February 14 and 23	Attikuan	from 21 to 23‰	from 21 to 23‰
February 14	Of Many Islands	5‰	from 13 to 17‰
February 14	Paul	< 1‰	< 1‰
South of the mouth of the La Grande Rivière			
February 14 and 20	Tees	1‰	1‰
February 14	Dead Duck	> 15‰	> 15‰

4.3 Relation between the extent of the plume and the La Grande Rivière discharge

The most notable difference between the 1993 and 1995 results is a shrinkage of the plume toward the south and the east of the 20‰ isohaline of the northern portion of the plume in February 1995, for similar discharges (Table 5). In 1993, the La Grande Rivière plume reached the plumes of the Kapsaouis and Roggan rivers in the north. However, the shrinkage to the south in 1995 was not observed for the core of the plume (5‰ isohaline) or the front (10‰ isohaline). Also noteworthy is the small extent of the plume in April 1995 for discharges similar to 1987 and 1989.

Table 5 Linear extent of the winter plume from the mouth of the La Grande Rivière in 1993 and 1995

Year	La Grande Rivière discharge (m^3/s)	Distance under 5‰ (km)		Distance under 10‰ (km)		Distance under 20‰ (km)	
		North	South	North	South	North	South
February 1993	4,600	40	30	45	-	70	-
February 1995	4,400	40	15	45	25	50	30
April 1995	3,300	-	-	-	-	30	20
February 1987	3,700	30	25	40	-	50	-
February 1989	4,000	-	35	-	40	-	45

In comparison with 1987 and 1989, the surface area of the plume core increased by about 400 km^2 for an increase of the discharge in the order of 1,000 m^3/s, while the total surface area is comparable or 75% greater, whether considering the February 1995 or February 1993 data (Table 6). For April 1995, the total surface area of the plume would be reduced by half for a decrease in discharge of 400 to 700 m^3/s.

When comparing the plumes of the baseline conditions (1987 and 1989) with those following the commissioning of La Grande-2-A and La Grande-1 (1993 and 1995), it is obvious that the freshwater discharge is not the only factor regulating the surface area of the La Grande Rivière plume.

Table 6 Surface area of the La Grande Rivière winter plume delineated by the 5, 10 and 20‰ isohalines in 1987, 1989, 1993 and 1995

Date	La Grande Rivière discharge (m^3/s)	Surface area (km^2)		
		5‰ isohaline	10‰ isohaline	20‰ isohaline
February 1993	4,600	1,637	2,055	3,200 to 3,500
February 1995	4,400	1,350 to 1,600	-	2,100 to 2,800
April 1995	3,300	-	-	± 1,000
February 1987 and 1989	3,700 to 4,000	1,200	-	2,000

The study of 8 plumes from 4 rivers of James Bay and Hudson Bay (La Grande River, Great Whale River, Little Whale River, Nastapoka River) led to an empirical model relating the freshwater discharge to the surface area of the plume (CSSA, 1993c, 1995a). The model is valid only for total ice cover conditions and for mixing conditions found in James Bay and Hudson Bay.

Table 7 compares the results of the surface areas calculated by the empirical model applied to the La Grande River plume and the surface areas measured under 20‰. The model correctly estimates the surface area of the plume when it is entirely located under the ice, as in 1980 and 1993. It has already been mentioned that the surface area of the plume in 1987 is underestimated since the field measurements were conducted only from the landfast ice. The surface area of the plume in 1995 is much smaller than expected, without any sampling biases occurring.

4.4 Influence of the wind on the extent of the plume in 1993 and 1995

The freshwater plumes are much smaller in open water than under the ice, even for smaller winter river discharges. The wind appears to be a major mixing agent.

Table 7 Calculated and measured surface areas of the La Grande Rivière winter plume at 20‰ for discharges ranging from 1 700 m^3/s to 4 400 m^3/s

Date	La Grande River discharge (m^3/s)	Calculated (km^2)	Measured (km^2)	Deviation (%)
1980	1,700	1,680	1,600	- 5
1987	3,700	2,800	2,000	- 29
1993	4,600	3,240	3,200 to 3,500	+1 to + 8
1995	4,400	3,150	2,100 to 2,800	- 33 to – 11

Several authors have mentioned the recurring occurrence of an open water coastal lead off the landfast ice (e.g. Croal and Tapiatic, 1974; Freeman et al., 1982; Ingram and Larouche, 1987; Messier et al., 1989). The extent of landfast ice is not related to the discharge of the La Grande Rivière (Ingram and Larouche, 1987) and the occurrence of the coastal lead is influenced directly by wind conditions and, to a lesser extent, by air temperature.

The winds blowing offshore from the land tend to push the ice floes offshore and create open water areas. The winds more or less following the coastline, originating from the north or the northwest, tend to create smaller open water leads. Finally, the winds blowing from the sea tend to pile up drifting ice floes along the edge of the landfast ice.

The February 1993 plume was much larger than the February 1995 plume, for similar discharge conditions in the La Grande Rivière. Similarly, the surface area of the April 1995 plume was two times smaller than the 1987 plume, for similar river discharges.

The February 1993 plume was measured under total ice cover, which favours the expansion of the plume (CSSA, 1993d,e), while in February 1995 there were open water zones allowing a greater freshwater-saltwater mixing rate, and inducing a smaller plume (CSSA,1995b). In April 1995, the field survey team observed a fairly large concentration of drifting floes.

Thus, large open water zones, such as a wide coastal lead or a large polynia, induce a greater mixing rate of the surface freshwater with the underlying saltwater layer, resulting in a smaller La Grande Rivière winter plume.

5. Conclusion

The Environmental Monitoring Program and the additional La Grande Rivière winter plume studies (1987-2000) have validated the predictions of the impact study. These predictions were limited to defining the length of coastline and the surface area of the plume, delineated by the 10‰ isohaline (limit of the front) and the 20‰ isohaline (limit of the plume).

After the commissioning of the La Grande-2-A and La Grande-1 generating stations, the total surface area of the plume varied from 3,200 km^2 to 3,500 km^2, for a typical discharge of 4,600 m^3/s in February 1993, and from 2,100 km^2 to 2,800 km^2, for a discharge of 4,400 m^3/s in February 1995. The empirical model predicted a surface area of 3,000 km^2 for a discharge of 4,300 m^3/s (Roche, 1983b, 1984).

For comparison purposes, the total surface area of the plume in 1987 and 1989, for discharges of 3,700 m^3/s to 4,000 m^3/s, was estimated at 2,000 km^2. In 1980, it was 1,600 km^2 for a discharge of 1,700 m^3/s. Therefore, by increasing the discharge of the La Grande Rivière from 1,700 m^3/s to 4,600 m^3/s, the surface area of the plume went from 1,600 km^2 to 2,100 km^2 or 3,500 km^2, depending on the minimum or maximum expansion conditions observed.

The results of the 1987 and 1989 surveys suggest that the empirical model produced for the impact study tends to overestimate the expansion of the plume toward the north and to underestimate its expansion toward the south (Hydro-Québec and SEBJ, 1985, 1986). A new relation between the surface area of the plume under the ice and the discharge of the La Grande Rivière was developed in 1993 (CSSA, 1993c; Messier and Anctil, 1996). This new model shows a good adequacy between the predicted and recorded surface areas if, and only if, the plume is totally under the ice.

The 1993 and 1995 surveys have shown the great variability of the plume surface area under the influence of the wind, which affects the size of open water areas and the mixing rate of freshwater with saltwater. The occurrence of large open water zones would result in a greater mixing rate of surface freshwater with underlying saltwater layers, inducing a reduction of the surface area of the La Grande Rivière winter plume.

The size of the coastal lead at the edge of the shore fast ice along the east coast of James Bay depends mostly on wind conditions and, to a lesser extent, on air temperatures, but not on the La Grande Rivière discharge rate.

A warm spell seems to result in the occurrence of larger open water areas. The effects of a warm spell and the dispersion of the ice floes were studied by Lepage and Ingram (1991) off Great Whale River. The authors observed that the combined action of winds, drifting floes and waves in open water zones led to a radical modification of the stratification of the water column. The column goes from a two layer system, before ice break-up, to a homogeneous non stratified layer over the first 10 m of the water column.

The variability of the extent of the plume is inherent to the physical conditions prevailing along the east coast of James Bay. In February 1993, its extent varied by 300 km^2 in nine days, while in February 1995, it varied by 700 km^2 in 15 days. These variations of surface area correspond to variations in the discharge of 136 m^3/s and 490 m^3/s respectively. A difference of 700 km^2 was also estimated in 1989 to account for the advances and withdrawals of the isohalines in the southern portion of the plume. It was not possible to clearly identify the influence factors, as there are several interacting elements. The tide is one of the major factors affecting the mixing rate. From low tide to high tide, the current velocities double, which means that the mixing rate is multiplied by 8, i.e. velocity power 3 (Messier et al., 1989).

In addition to the study of the La Grande Rivière winter plume, the surveys of 1987 to 1995 confirmed several hypotheses proposed during the baseline conditions period. Thus, other rivers, such as the Au Castor, Kapsaouis and Roggan rivers, form coastal plumes. In February 1993, the La Grande Rivière plume reached the Roggan River plume in the north. Also, the numerous bathymetric breaks (shoals, islands), as in the Bay Of Many Islands, result in a greater mixing rate of the plume surface waters with the deeper saltwater layer.

Finally, it was demonstrated, for the third time, that the inputs of sestonic elements and nutrients from the La Grande Rivière to the coastal waters of James Bay are not significant in winter. This river does not supply the nutrients which remain deficient in the waters of James Bay, both in the winter and the summer.

The monitoring of the La Grande Rivière plume shows that the variations of its discharge rate must be very large in order to delineate the dimensions and structure of its winter plume and to demonstrate that they are related only to the variations of the river discharge. The natural variability of the dynamics of a river plume is such that the expected physical modifications of the plume must be well above the natural physical variations.

In conclusion, two conditions must be met for the monitoring of a winter plume to be necessary and conclusive. First, the expected modifications to the river discharge must be greater than the range of natural discharge variations. Second, critical habitats or resources must be significantly threatened by these modifications, which was not the case on the northeast coast of James Bay, as demonstrated by the marine eelgrass monitoring program.

6. Bibliography

CROAL, J.P., TAPIATIC, S., 1974. *Field Report Winter Oceanography, James Bay, 1974*. Environment Canada, Marine Science Directorate, Central Region, Canada Centre for Inland Waters, Unpublished Report. 85 p.

CSSA, 1993a. *Complexe La Grande. Étude des caractéristiques du panache de la Grande Rivière au cours de l'hiver 1993; rapport de données sur le mercure et le méthylmercure.* Report by CSSA Consultants ltée for Société d'énergie de la Baie James. 7 p. and appendices.

CSSA, 1993b. *Algues sympagiques de la côte est de la baie James; La Grande Rivière – 1993*. Report by CSSA Consultants ltée for Société d'énergie de la Baie James. 36 p. and appendix.

CSSA, 1993c. *Complexe Grande-Baleine. Analyses objectives et descriptives de huit panaches d'eau saumâtre sous couverture de glace.* Report by CSSA Consultants ltée for Hydro-Québec. 45 p. and appendix.

CSSA, 1993d. *Étude du panache de La Grande Rivière durant l'hiver 1993; rapport de mission de la campagne de février 1993.* Report by CSSA Consultants ltée for Société d'énergie de la Baie James. 21 p.

CSSA, 1993e. *Étude du panache de La Grande Rivière durant l'hiver 1993; rapport de mission de la campagne d'avril 1993.* Report by CSSA Consultants ltée for Société d'énergie de la Baie James. 32 p.

CSSA, 1995a*. Complexe La Grande. Mesures océanographiques dans la baie James en 1995; étude du panache de La Grande Rivière sous couverture de glace*. Report by CSSA Consultants ltée for Société d'énergie de la Baie James. 70 p.

CSSA, 1995b. *Mesures océanographiques dans la baie James en 1995; rapport de données des missions de février et d'avril 1995.* Report by CSSA Consultants ltée for Société d'énergie de la Baie James. 8 p. and appendices.

FREEMAN, N.G., FLEMMING, B.M., 1982. *James Bay / La Grande oceanographic data report winter 1980*. Volumes I et II. Burlington (ON): Bayfield Laboratory Data Report Series 82-4 et 82-5.

FREEMAN, N.G., ROFF, J.C., PETT, R.J., 1982. Physical, chemical, and biological features of river plumes under an ice cover in James and Hudson Bays. *Le Naturaliste canadien,* vol. 109 (1982), p. 745-764.

HYDRO-QUÉBEC ET SEBJ, 1985. *Suréquipement de l'aménagement La Grande 2; rapport sur les études d'avant-projet. Volume 3: Répercussions sur l'environnement*. Hydro-Québec and Société d'énergie de la Baie James. 506 p.

HYDRO-QUÉBEC ET SEBJ, 1986. *Suréquipement de l'aménagement La Grande 2; rapport sur les études d'avant-projet. Informations complémentaires*. Hydro-Québec and Société d'énergie de la Baie James. Multiple pagination.

INGRAM, R.G., LAROUCHE, P., 1987. Changes in the under-ice characteristics of La Grande Rivière plume due to discharge variations. *Arctic*, vol. 25 (1987), p. 242-250.

LAROUCHE, P., 1984. *Données de la campagne océanographique La Grande, hiver 1984.* Unpublished photocopied document.

LEGENDRE, L., INGRAM, R.G., POULIN, M., 1981. Physical control of phytoplankton production under sea ice (Manitounuk Sound, Hudson Bay). *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 38 (1981), p. 1385-1392.

LEPAGE, S., INGRAM, R.G., 1991. Variation of upper dynamics during ice break-up of the seasonal ice cover in Hudson Bay. *Journal of Geophysical Research,* vol. 96 (1991), p. 12711-12724.

MESSIER, D., 2002. *Suivi environnemental des projets La Grande-2-A et La Grande-1. Le panache de La Grande Rivière.* Rapport synthèse pour la période 1987-2000. Direction Barrages et Environnement, Hydro-Québec Production. 73 p. and appendices.

MESSIER, D., ANCTIL, F., 1996. *On under-ice river plumes in James and Hudson Bays*. In: Leclerc, M. et al. (Eds.) Proceedings of the second IAHR Symposium on Habitats Hydraulics - Ecohydraulics 2000, 1996, Québec (QC). INRS-eau, Fédération québécoise pour le Saumon atlantique and International Association for Hydraulic Research. p. A447-A458.

MESSIER, D., LEPAGE, S., DE MARGERIE, S., 1989. Influence du couvert de glace sur l'étendue du panache de La Grande Rivière (baie James). *Arctic*, vol. 42 (1989), p. 278-284.

ROCHE, 1983a. *Étude des caractéristiques physiques et physico-chimiques de l'épanchement et du mélange d'eau douce de La Grande Rivière dans la baie James*. Report by Roche Associés ltée for Société d'énergie de la Baie James. 140 p. and appendices.

ROCHE, 1983b. *Études océanographiques de la côte est de la baie James. Tome 1. Influence du régime hydrologique sur le mouvement des masses d'eau à l'embouchure de La Grande Rivière*. Report by Roche Associés ltée for Société d'énergie de la Baie James. 55 p.

ROCHE, 1984. *Répercussions biophysiques dans l'estuaire de La Grande Rivière et sur la côte nord-est de la baie James. Volume 1: Calibration du modèle de distribution des isohalines de surface en hiver*. Report by Roche Associés ltée for Société d'énergie de la Baie James. 32 p.

SEBJ, 1990. *Suivi environnemental du projet de La Grande-2A. Volume 2. Plan directeur du suivi*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 91 p.

APPENDIX 1

List of Summary Reports of the Environmental Monitoring Programs at the La Grande Complex, Phase I (1977-1986)

Environmental Monitoring Network

Boucher, R., Roy, D., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: poissons.* Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 119 p.

Boudreault, J., Roy, D., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: macroinvertébrés benthiques.* Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 102 p.

Dusseault, D., Boudreault, J., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: description du milieu*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. n. p.

Messier, D., Roy, D., Lemire, R., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: évolution du mercure dans la chair des poissons*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 156 p.

Roy, D., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: zooplancton.* Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 92 p.

Roy, D., Boudreault, J., Boucher, R., Schetagne, R., Thérien, N., 1986. *Réseau de surveillance écologique du complexe La Grande 1978-1984: synthèse des observations*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. n. p.

Schetagne, R., Roy, D., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: physico-chimie et pigments chlorophylliens*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 158 p.

Schetagne, R., Roy, D., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: physico-chimie et pigments chlorophylliens. Annexe 1: région de La Grande 2*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. n. p.

Schetagne, R., Roy, D., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: physico-chimie et pigments chlorophylliens. Annexe 2: région d'Opinaca*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. n. p.

Schetagne, R., Roy, D., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: physico-chimie et pigments chlorophylliens. Annexe 3: région de Caniapiscau*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. n. p.

Thérien, N., 1985. *Réseau de surveillance écologique du complexe La Grande 1978-1984: modélisation et simulation*. Faculté des Sciences appliquées, Université de Sherbrooke and Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 161 p.

Resources and Habitats

Huot, J., Paré, M. 1986. *Surveillance écologique du complexe La Grande: synthèse des études sur le caribou de la région de Caniapiscau*. Université Laval and Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 214 p.

Julien, M., 1986. *Surveillance écologique du complexe La Grande : synthèse des études sur le lièvre et les lagopèdes*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 214 p.

Julien, M., Laperle, M., 1986. *Surveillance écologique du complexe La Grande: synthèse des études sur la sauvagine*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 214 p.

Julien, M., Nault, R., 1985. *Surveillance écologique du complexe La Grande: synthèse des études sur l'orignal*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 117 p.

Julien, M., Lemieux, M., Ouzilleau, J., 1985. *Surveillance écologique du complexe La Grande: synthèse des études sur les zones riveraines*. Le Groupe Dryade and Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 214 p.

Specific Regions

Lalumière, R., Le Jeune, R., Boudreault, A., 1985. *Répercussions d'une réduction de débit sur les rivières Caniapiscau et Koksoak*. Report by Gilles Shooner inc. for Groupe d'étude conjoint Caniapiscau-Koksoak, Société d'énergie de la Baie James. 117 p.

Messier, D., 1985. *Modifications océanographiques physiques et biologiques à la suite de l'aménagement du complexe La Grande*. Direction Ingénierie et Environnement, Société d'énergie de la Baie James. 127 p.

Messier, D., 1985. *Synthèse des modifications physiques dans l'estuaire de la rivière Koksoak suite à la coupure de la rivière Caniapiscau*. Groupe d'étude conjoint Caniapiscau-Koksoak, Société d'énergie de la Baie James. 54 p. and appendices.

SEBJ-SOTRAC, 1985. Étude des effets du détournement des rivières Eastmain et Opinaca en aval des ouvrages de dérivation ; synthèse des résultats du suivi environnemental de 1980 à 1984. Société d'énergie de la Baie James and Société des travaux de correction du complexe La Grande. 256 p.