SEDIMENT QUALITY AND DREDGING ACTIVITIES IN THE ST. LAWRENCE RIVER

Restoration Technologies Division
Technology Development Branch
St. Lawrence Centre
Environment Canada

MARCH 1993
REVISED OCTOBER 1993

NOTICE OF REVIEW AND COMMENTS

This report was reviewed by the St. Lawrence Centre, Conservation and Protection, Environment Canada, which authorized its publication. The authorization does not necessarily mean the contents of the report reflect opinions and policies of Environment Canada.

Comments about the content of the report may be sent to the following address:

Technology Development Section
Environmental Protection Branch
685 Cathcart Street
8th Floor
Montréal, Québec
H3B 1M6
(514) 283-7000

This guide should be cited as follows:

St. Lawrence Centre (1993). *Sediment Quality and Dredging Activities in the St. Lawrence River.* By Lucie Olivier and Jacques Bérubé. Technology Development Branch. Cat. No. En 153-12/1993E.

Cat. No. En 153-12/1993E
ISBN 0-662-98142-1

PERSPECTIVE DE GESTION

Le présent rapport se rattache au Plan d'action Saint-Laurent. Par sa publication, la Direction du développement technologique poursuit un de ses objectifs qui consiste à développer et fournir aux intervenants en environnement divers outils d'évaluation de la qualité des sédiments du Saint-Laurent.

MANAGEMENT STATEMENT

This report was drafted as part of the St. Lawrence Action Plan. One of the goals of the Technology Development Branch of the St. Lawrence Centre is to develop tools to evaluate the quality of sediment in the St. Lawrence River and to make the tools available to those working to protect the environment. The report was published to help meet this goal.

WORK GROUP

A work group under the direction of René Rochon, Chief, Restoration Technologies, was formed for the project. Lucie Olivier was in charge of the project and the data bank and wrote part of the report. She was assisted by Luc Giroux (data bank management, data processing and map generation), Jacques Bérubé (drafting of the report), François Boudreault (map generation) and Monique Simond (editing and publishing).

ACKNOWLEDGEMENTS

The authors would like to thank everyone who supplied information for the data bank. Special thanks go to Stéphane Lorrain and Jean-René Michaud for their valuable feedback.

RÉSUMÉ

Le présent rapport évalue la qualité des sédiments du Saint-Laurent et détermine les tendances entre 1976 et 1989 lorsque les données pertinentes sont disponibles. Sept métaux ont retenus l'attention : il s'agit du cadmium, du chrome, du cuivre, du mercure, du nickel, du plomb et du zinc. Les sites qui présentent les plus fortes teneurs en métaux lourds sont identifiés et on a tenté de mettre ces derniers en relation avec les apports toxiques provenant de la section internationale du Saint-Laurent, des industries prioritaires, des tributaires et des municipalités riveraines dans la mesure où l'information était disponible.

La contamination dans le tronçon le plus amont de la section québécoise du Saint-Laurent, dont la composante principale est le lac Saint-François, a fortement baissé entre 1976 et 1989, principalement en ce qui concerne le cuivre, le chrome, le mercure, le nickel et le cadmium. Alors qu'en 1976 des problèmes majeurs étaient notés principalement en aval de Cornwall, dans la partie nord de la fosse de Saint-Zotique, à proximité de l'île aux Chats et dans la rivière Saint-Charles, la situation s'est, dans l'ensemble, grandement améliorée. En 1989, le lac Saint-François a été considéré relativement peu contaminé : aucune teneur ne dépassait plus le critère de qualité de niveau 3 à partir duquel les effets sur l'environnement sont jugés majeurs, et plusieurs médianes se situaient au niveau des teneurs naturelles. Les secteurs qui ont subi la plus grande amélioration sont l'aval de Cornwall et de Massena ainsi que la partie nord de la fosse de Saint-Zotique. Les teneurs médianes du versant nord sont demeurées supérieures à celles du versant sud et certaines régions (aval de Cornwall, embouchure de la rivière aux Raisins, hauts-fonds du tiers amont et fosse de Saint-Zotique) ont présenté des teneurs en certains contaminants plus élevées que la médiane du lac.

Cette baisse de contamination a été reliée à une importante réduction des rejets dans le secteur de Cornwall suite à la mise en application de la réglementation sur les effluents liquides industriels ainsi qu'à des interventions dans la région de Massena visant à réduire les apports. Elle démontre l'importance des sources industrielles de la région de Cornwall dans la contamination du lac Saint-François. Dans ce sous-système il reste à préciser la qualité des sédiments du secteur de l'île aux Chats et de la rivière Saint-Charles dont la contamination est de source locale, ainsi que du canal de Beauharnois et du tronçon international du Saint-Laurent.

En ce qui concerne le lac Saint-Louis, de très importants problèmes de contamination par le mercure étaient mis en évidence à la fin des années 1970 dans la portion sud-est du lac (à l'embouchure de la rivière Saint-Louis et au sud des îles de la Paix) ainsi que dans la Baie de Valois. Un lien étroit a été établi entre la contamination par le mercure de la rivière Saint-Louis et les rejets industriels dans la rivière du même nom. Ce plan d'eau était aussi fortement contaminé par le cadmium tandis que son enrichissement pour les autres paramètres variait de faible à modéré.

La qualité des sédiments du lac Saint-Louis s'est généralement améliorée entre 1976 et 1985. L'embouchure de la rivière Saint-Louis était, en 1976, la zone la plus contaminée du lac Saint-Louis; en 1984-1985 elle s'est révélée être celle où l'amélioration

a été la plus marquée. Les substances pour lesquelles une amélioration a été notée sont : le mercure, le cuivre, le zinc, le cadmium et le nickel. Suite à une diminution des rejets des industries de la région de Beauharnois, certains apports ont diminué de façon notable, notamment ceux en mercure. En 1984-1985, ce secteur demeurait néanmoins très contaminé par le mercure.

La qualité des sédiments du sud des îles de la Paix s'est également améliorée au cours de la décennie. L'amélioration s'est fait sentir pour le mercure, le cadmium et le nickel. La concentration des autres paramètres est demeurée stable dans le milieu. Cette région est influencée par les apports des industries de la région de Beauharnois et ceux du fleuve. Les résultats suggèrent que la diminution des rejets à Beauharnois aurait eu une influence moins marquée sur la qualité des sédiments de ce secteur qu'à l'embouchure de la rivière Saint-Louis.

La qualité des sédiments du centre du lac s'est aussi légèrement améliorée au cours de la décennie. Les paramètres qui ont connu une amélioration sont le mercure, le zinc et le cadmium. La concentration des autres paramètres est demeurée stable ou, dans le cas du plomb, s'est détériorée légèrement. Cet environnement est influencé par les eaux du fleuve, qui transportent les charges du sous-système 1 et des Grands Lacs, et celles de la rivière des Outaouais, qui sont également chargées en contaminants. Une partie de ces charges ne s'y dépose cependant pas et transite vers l'aval.

À l'exemple des autres régions du lac Saint-Louis, la qualité des sédiments de la Baie de Valois s'est améliorée au cours de la décennie. La teneur médiane du mercure, du cuivre, du cadmium, du chrome et du nickel a diminué tandis que celle du plomb et du zinc s'est accrue. La contamination de ce secteur est essentiellement attribuée aux rejets des émissaires de l'ouest de l'île de Montréal et aux apports de la rivière des Outaouais.

À Beaconsfield, au nord de l'île Dowker, à la sortie de l'exutoire Sainte-Anne ainsi qu'à l'exutoire Vaudreuil, diverses caractérisations menées entre 1984 et 1987 ont permis de mettre en évidence une contamination forte ou modérée par le mercure, le cuivre, le zinc, le plomb et le chrome, attribuée aux rejets des municipalités situées dans l'ouest de l'île de Montréal ainsi qu'aux apports de la rivière des Outaouais. La contamination de ces zones a été attribuée à cette dernière.

Entre 1976 et 1987, la contamination du Petit bassin de La Prairie s'est accrue de façon perceptible pour le zinc, le plomb et le chrome tandis qu'elle a diminué pour le cadmium et est demeurée stable pour le mercure, le cuivre et le nickel. Il n'y a donc pas de tendance uniforme dans l'évolution temporelle de la distribution des contaminants dans ce plan d'eau. La contamination des sédiments du Petit bassin de La Prairie en ce qui concerne le chrome, le cuivre, le nickel et le plomb mérite d'être soulignée à cause de son importance; elle est nettement plus élevée qu'ailleurs dans le fleuve, en particulier à l'embouchure de l'émissaire de Candiac. Le patron de répartition des contaminants suggérait que la principale source de certains métaux (mercure, plomb, cadmium, nickel) était située à l'amont tandis que pour le cuivre, le zinc et le chrome, l'importance des sources locales semblait prédominer. Le Petit bassin de La Prairie se situe dans un environnement très urbanisé et industrialisé. Pendant la décennie 1976-

1987, sa qualité sédimentaire n'a pas subi d'amélioration comme dans les secteurs amont mais a, au contraire, plutôt eu tendance à se détériorer.

En ce qui concerne le Port de Montréal, d'importants problèmes de contamination ont été décelés pour la plupart des métaux lourds.

Dans la partie aval du sous-système, la contamination du delta de Sorel et du lac Saint-Pierre a évolué de 1976 à 1986 suivant généralement les mêmes tendances que dans le Petit bassin de La Prairie. Elle s'est accrue pour le zinc, le plomb, le cuivre et le chrome; elle a diminué pour le cadmium et est restée stable pour le mercure et le nickel. En 1986, le lac Saint-Pierre était dans l'ensemble faiblement ou modérément contaminé par les métaux traces selon les paramètres concernés. Cependant, l'embouchure de la rivière Richelieu et la portion sud du delta de Sorel et du lac situées dans le panache des effluents des industries de Sorel-Tracy se sont avérées beaucoup plus contaminées que le reste du lac pour tous les paramètres à l'exception du cadmium.

L'estuaire fluvial allant de Pointe-du-Lac à l'aval de l'île d'Orléans a été peu caractérisé au plan physico-chimique. Les données disponibles indiquent cependant une tendance à l'augmentation des teneurs en cuivre, plomb et zinc au cours de la période de référence; à la diminution des teneurs en cadmium et chrome et finalement au maintien de niveaux stables pour le mercure. Sauf pour le chrome, les tendances ont été les mêmes à l'embouchure de la rivière Saint-Charles (un site qui n'a pas été dragué) que dans la Traverse Nord de l'île d'Orléans (un site dragué régulièrement). La contamination de la région de Trois-Rivières serait principalement due aux apports de la rivière Saint-Maurice; celle de l'embouchure de la rivière Saint-Charles et des rives de Lévis et Lauzon serait plutôt de source locale, tandis que celle de la Traverse Nord serait liée aux apports de l'amont ainsi qu'aux apports locaux.

Les tendances spatiales relativement à la distribution des contaminants en eaux douces, ont montré une augmentation de la majorité des paramètres (cuivre, zinc, plomb, chrome et nickel) du lac Saint-François au Petit bassin de La Prairie où ils ont atteint leur valeur maximale, puis une diminution graduelle à l'aval. En ce qui concerne le mercure, la plus forte médiane s'applique au lac Saint-Louis; puis elle a décru progressivement à l'aval, montrant la même tendance à la baisse que les contaminants précédents. La répartition spatiale du cadmium est impossible à établir puisque dans certains secteurs la limite de détection retenue était élevée (1,00 μ/g).

Dans le Saint-Laurent marin, les concentrations les plus élevées de cuivre, plomb et zinc se rencontrent dans les pélites (boues) du moyen estuaire. En gagnant la mer, leur concentration décroît comme le fait également l'apport naturel et anthropique de matière particulaire en suspension. La tendance inverse s'observe pour le nickel; quant au chrome, il se maintient dans l'estuaire maritime et le golfe à un niveau plus élevé que dans le moyen estuaire et le fjord du Saguenay.

Les métaux traces du moyen estuaire se retrouvent en plus forte concentration dans la fraction fine de quelques zones de dépôt d'où peu de matière peut s'échapper. Par rapport aux critères de qualité, les concentrations moyennes qu'on y retrouve correspondent aux teneurs naturelles en nickel et traduisent une faible contamination par le chrome, par le cuivre et par le plomb et une contamination modérée par le zinc.

Une importante contamination par du mercure d'origine anthropique a été décelée dans les sédiments de surface du fjord du Saguenay; entre 1940 et 1962, la contamination s'est globalement accrue d'un facteur de 40 par rapport à la teneur naturelle de ce milieu. Ce problème n'a pas eu d'équivalent dans l'estuaire maritime ni dans le Golfe du Saint-Laurent. Suite à la mise en application de mesures de réduction des rejets industriels, le mercure des sédiments de surface du bassin supérieur de fjord a fortement diminué. En ce qui concerne les autres métaux traces, une augmentation d'origine anthropique des teneurs en cuivre (15 p. 100) en plomb (40 p. 100) et en zinc (15 p. 100) a été observée entre 1940 et 1976. Contrairement au mercure, ces teneurs n'ont cessé de s'accroître depuis 1940, suggérant que d'importantes sources de ces métaux n'étaient pas taries. Les concentrations moyennes du fjord du Saguenay correspondent aux teneurs naturelles en cuivre et en nickel, à un faible enrichissement en chrome et en zinc, et à un enrichissement modéré en plomb.

Une contamination modérée par du mercure d'origine anthropique a été observée dans les sédiments de surface de l'estuaire maritime avant 1975 et sa distribution a été associée au patron de dépôt de la matière organique originant du Saguenay. Toutefois des mesures effectuées une décennie plus tard ont indiqué qu'elle avait tendance à diminuer. Les teneurs en mercure mesurées dans le Golfe du Saint-Laurent sont faibles et ne présentent qu'un faible enrichissement par rapport aux teneurs naturelles de ce milieu. Ce paramètre ne montre pas de patron clair de dépôt ni d'évidence que le mercure d'origine anthropique ait atteint cet environnement. En ce qui concerne les autres métaux, les sédiments de l'estuaire maritime présentent en moyenne un faible enrichissement en chrome, en plomb et en zinc tandis que ceux du golfe présentent un faible enrichissement en chrome. Les autres paramètres se situent au niveau des teneurs naturelles. L'enrichissement le plus marqué en cuivre, en plomb et en zinc se rencontre dans les sédiments fins des vallées centrales et de certains plateaux tandis que la plupart des plateaux sableux, exception faite de ceux du nord d'Anticosti, sont faiblement contaminés par ces métaux.

Les activités de dragage dans le chenal de navigation, les ports et les marinas ont entraîné entre 1983 et 1991 le déplacement de quelque 5 500 000 m^3 de sédiments, ce qui représente environs 617 000 m^3 par année. La Gaspésie vient en tête pour ce qui est du nombre de dragages avec 52 p. 100 de tous les dragages pratiqués sur le fleuve, soit 266 sur un total de 507. Viennent ensuite les îles de la Madeleine, le moyen estuaire, l'estuaire fluvial et le secteur de l'île d'Orléans. D'autre part la plus forte moyenne de matériaux déplacés par dragage (44 000 m^3) revient au secteur de l'île d'Orléans.

Les principales portions du chenal de navigation qui sont sujettes à une forte sédimentation et qui en conséquence, font l'objet de dragages d'entretien tous les ans ou presque sont certaines courbes du lac Saint-Pierre, l'aire de mouillage de Batiscan, la courbe de Bécancour, la traverse de Cap-Santé, l'aire de mouillage de Portneuf et la Traverse Nord de l'île d'Orléans. De plus cinq localités de l'estuaire moyen, 18 de la Gaspésie et 9 des îles de la Madeleine font l'objet de dragages d'entretien très fréquents.

Le suivi de la qualité des sédiments du fleuve au cours d'une décennie a permis de noter une amélioration de la qualité des sédiments de surface pour sept métaux (cadmium, chrome, cuivre, mercure, nickel, plomb et zinc) lorsque les sources de contamination sont taries. Bien que les mécanismes régissant cette restauration soient mal connus, ce facteur devra néanmoins être pris en considération lors de la priorisation des activités de restauration du milieu aquatique.

ABSTRACT

This report describes sediment quality in the St. Lawrence River, identifying trends between 1976 and 1989 when adequate data are available. The report focuses on seven metals: cadmium, chromium, copper, mercury, nickel, lead and zinc. Sites with highest concentrations of heavy metals are identified, and (whenever data are available) high concentrations are related to toxic input from targeted industrial plants, tributaries, riverside municipalities and the international section of the river.

Contamination of the upper Québec stretch of the St. Lawrence River (of which Lake St. Francis is the main component) decreased significantly between 1976 and 1989--contamination by copper, chromium, mercury, nickel and cadmium in particular. Whereas major problems were detected in 1976 (mainly downstream of Cornwall, in the northern part of the St. Zotique basin, around Ile aux Chats and in the St. Charles River), by 1989 the situation had generally improved a great deal. Lake St. Francis was relatively uncontaminated by 1989: nowhere did contaminant levels exceed Toxic Effect Threshold (TET) and several medians were natural background levels. The biggest improvements were downstream of Cornwall and Massena, and in the northern part of the St. Zotique basin. Median levels on the north side of the lake remained higher than those on the south side, and concentrations of certain contaminants were higher than the median of the lake in certain areas (downstream of Cornwall, at the mouth of Raisin River, in the shallows of the upstream third of the lake and in the St. Zotique basin).

Contamination diminished because of major decreases in discharges to the Cornwall area with enforcement of regulations on industrial liquid effluents and measures in the Massena region to reduce toxic input. The significant decrease in contamination demonstrates the major role played by industrial plants in the Cornwall area in contaminating Lake St. Francis. In this subsystem, only the quality of sediment in the Île aux Chats and St. Charles River area (where contamination is from local sources) as well as in the Beauharnois Canal and the international section of the St. Lawrence River remains to be determined.

In the late 1970s, major mercury contamination was detected in Valois Bay and in the southeastern part of Lake St. Louis (at the mouth of the St. Louis River and south of Îles de la Paix). Mercury contamination of the St. Louis River was found to be closely linked to industrial discharges to the St. Louis River, which was also highly contaminated by cadmium. Enrichment by other heavy metals ranged from low to moderate.

Sediment quality in Lake St. Louis generally improved between 1976 and 1985. The most contaminated area of Lake St. Louis in 1976 was the mouth of the St. Louis River, yet this was where the most marked improvement was noted in 1984-1985. Contamination by mercury, copper, zinc, cadmium and nickel decreased. With the decrease in industrial discharges to the Beauharnois region, surface sediment contamination by certain metals--mercury in particular--diminished appreciably. Lake St. Louis was nonetheless still highly contaminated by mercury in 1984-1985.

Sediment quality also improved south of Îles de la Paix over the last decade: mercury, cadmium and nickel contamination decreased. Concentrations of the other metals studied remained stable. This area is affected by input from industrial plants in the Beauharnois area as well as input from the upstream reaches of the St. Lawrence. Sediment survey results suggest the decrease in discharges at Beauharnois did not affect sediment quality as much in this area as at the mouth of the St. Louis River.

Sediment quality also improved slightly in the centre of the lake over the last decade. Mercury, cadmium and zinc contamination decreased, and concentrations of the other heavy metals remained stable--except for that of lead, which increased slightly. This environment is influenced by waters from upstream reaches of the St. Lawrence, which transport contaminant loads from subsystem 1 and the Great Lakes, and by the waters of the Ottawa River, which are also heavily loaded with contaminants. The entire contaminant load is not however deposited here; some of it is transported downstream.

Sediment quality also improved in Valois Bay during the last decade. Median values of mercury, copper, cadmium, chromium and nickel decreased. Median values of zinc and lead increased however. Contamination of this area is mainly attributable to discharges from Montréal West Island outfalls and input from the Ottawa River.

Sediment characterization studies between 1984 and 1987 showed heavy or moderate contamination by mercury, copper, zinc, lead and chromium at Beaconsfield as well as north of Dowker Island, at the St. Anne channel outlet and in the Vaudreuil channel. The contamination was attributed to discharges from Montréal West Island municipalities as well as input from the Ottawa River.

Zinc, lead and chromium contamination of the lesser La Prairie basin increased appreciably between 1976 and 1987; cadmium contamination decreased, and mercury, copper and nickel contamination remained stable. In other words, there was no uniform temporal trend in contaminant distribution in this stretch. Chromium, copper, nickel and lead contamination of the sediment of the lesser La Prairie basin was especially pronounced, higher than elsewhere in the St. Lawrence, especially at the mouth of the Candiac outfall. Contaminant distribution patterns suggest the main sources of mercury, lead, cadmium and nickel contamination are upstream, and the main sources of copper, zinc and chromium contamination are local. The lesser La Prairie basin is in a very urbanized and industrialized area, and sediment quality here did not improve between 1976 and 1987, as it did upstream; in fact, it deteriorated.

Montréal harbour was found to be highly contaminated by most heavy metals.

Downstream, at the Sorel delta and in Lake St. Pierre, trends between 1976 and 1986 were generally similar to those in the lesser La Prairie basin: zinc, lead, copper and chromium contamination increased, cadmium contamination decreased, and mercury and nickel contamination remained stable. In 1986, Lake St. Pierre was generally slightly or moderately contaminated by trace metals, depending on the metal. Contamination by all metals except cadmium was however much greater at the mouth of the Richelieu River, in the southern part of the Sorel delta and in the plume of industrial effluents from Sorel-Tracy (in the southern part of the lake) than elsewhere in the lake.

There has been little physicochemical characterization of the riverine estuary (from Pointe du Lac to downstream of Île d'Orléans). Data available do nonetheless suggest an upward trend in copper, lead and zinc concentrations between 1976 and 1988, a downward trend in cadmium and chromium concentrations, and stable mercury levels. With the exception of chromium, trends were similar at the mouth of the St. Charles River (a site never dredged) and in the channel north of Île d'Orléans (dredged regularly). Input from the St. Maurice River is the main source of contamination of the Trois Rivières region. Local sources are mainly responsible for contamination of the St. Charles River and the Lévis and Lauzon nearshore. Contamination of the north channel is linked to input from upstream as well as local sources.

Spatial contaminant distribution trends in freshwater reaches of the river show an increase in copper, zinc, lead, chromium and nickel concentrations between Lake St. Francis and the lesser La Prairie basin, where they reach maximum levels before gradually decreasing downstream. Highest mercury median was detected in Lake St. Louis; mercury medians then decreased gradually downstream like those of the other metals. Spatial distribution of cadmium could not be identified because detection limit selected in some areas was too high (1.00 μ/g).

In saltwater reaches, highest concentrations of copper, lead and zinc were detected in the pelites (mud) of the upper estuary. Concentrations decrease seaward, as does suspended particulate input from natural and anthropogenic sources. The reverse is true of nickel. Chromium concentrations are higher in the lower estuary and the gulf than in the upper estuary and the Saguenay Fjord.

In the upper estuary, trace metals appear in highest concentrations in fine fractions of a few deposition zones from which very little material can escape. Average nickel concentrations are natural background levels; chromium, copper and lead contamination is slight; and zinc contamination is moderate.

Major contamination of surface sediment of the Saguenay Fjord by anthropogenic mercury was detected. Between 1940 and 1962, overall mercury contamination increased to forty times natural background. Nothing like this was encountered in the lower estuary or the Gulf of St. Lawrence. After measures were taken to reduce industrial discharges, mercury in surface sediment in the inner basin of the fjord decreased dramatically. As for other trace metals, anthropogenic increases in copper (15 percent), lead (40 percent) and zinc (15 percent) concentrations were detected between 1940 and 1976. Unlike mercury, concentrations of these metals have increased constantly since 1940, suggesting major sources of these metals have not been checked. In the Saguenay Fjord, average concentrations of nickel and copper are natural background levels, and there is slight chromium and zinc enrichment and moderate lead enrichment.

Moderate contamination by anthropogenic mercury was detected in surface sediment of the lower estuary before 1975, with mercury distribution corresponding to the pattern of deposition of organic matter originating in the Saguenay. Surveys a decade later indicated a downward trend, however. Mercury levels are low in the Gulf of St. Lawrence, only slightly above natural background levels. In addition, there is no clear mercury deposition pattern nor any evidence that anthropogenic mercury has reached this environment. As for the other metals, the sediment of the lower estuary is slightly to moderately enriched by chromium, lead and zinc and that of the gulf slightly enriched by chromium. Concentrations of other metals are natural background levels. The most pronounced enrichment by copper, lead and zinc was detected in the fine sediment of the central troughs and of certain shelves; most of the sandy shelves, apart from the one north of Anticosti, are however only slightly contaminated by these metals.

Between 1983 and 1991, some 5 500 000 m^3 of sediment (about 617 000 m^3 a year) were dredged from the shipping channel and from harbours and marinas. More dredging operations were conducted in the Gaspé (52 percent) than anywhere else along the river--266 of a total 507 operations. The Magdalen Islands came next, followed by the upper estuary, the riverine estuary and the Île d'Orléans area. Average amount of material dredged in anyone dredging operation was greater in the Île d'Orléans area (44 000 m^3) than anywhere else.

Main areas of the shipping channel where sedimentation is pronounced and where maintenance dredging is therefore required every year or almost every year are certain bends of Lake St. Pierre, the Batiscan anchorage, the Bécancour bend, the Cap Santé channel, the Portneuf anchorage and the channel north of Île d'Orléans. Maintenance dredging is also very frequent at five sites in the lower estuary, eighteen sites in the Gaspé and nine sites in the Magdalen Islands.

Monitoring of sediment quality in the St. Lawrence River has shown an improvement in the quality of surface sediment; contamination by seven metals (cadmium, chromium, copper, mercury, nickel, lead and zinc) decreased where sources of contamination were checked. Although the mechanisms governing the improvement are not well understood, the improvement should nevertheless be taken into account when setting priorities for aquatic environment restoration projects.

CONTENTS

FIGURES

TABLES

1 OBJECTIVES

The St. Lawrence River is one of the largest rivers in North America. From the Québec/Ontario border, it runs 2 100 km to the Atlantic Ocean, draining a catchment area of 1 320 000 km^2. At Québec City, freshwater discharge is about 12 200 m^3/s. The St. Lawrence River constitutes more than one percent of the earth's freshwater.

The St. Lawrence Centre decided to determine trends in sediment quality in the St. Lawrence River between 1976 and 1989. Sites with highest concentrations of heavy meals were identified and efforts were made, whenever data were available, to determine the relation between high concentrations and toxic input from targeted industrial plants, municipalities and the international section of the St. Lawrence.

Particle-size distribution data were also compiled and main sedimentation and erosion areas identified using available hydrodynamic and sedimentologic data and studies.

Dredging activities along the St. Lawrence River were reviewed to determine scope of dredging activities over time and at specific sites, susceptibility to sedimentation of private and public harbours and areas of the seaway and shipping channel where sedimentation is likely to occur.

2 RESEARCH, ANALYSIS AND REPORTING

2.1 Sediment data bank

The St. Lawrence Centre's Restoration Technologies Division has developed a data bank on dredging and sediment quality in the St. Lawrence River (Dragsed). Most physicochemical and particle-size data collected since the mid-1970s have been entered in the bank. In all, close to 90 000 pieces of raw data were drawn from about 100 scientific publications and technical reports. The bank also contains most quantitative data available on maintenance dredging of the shipping channel and the St. Lawrence Seaway and on building and maintenance of private and public harbours as well as data on a variety of industrial activities (installation of water intakes and outfalls, road construction and so forth).

Data entered in Dragsed were taken from publications, scientific articles, technical reports and environmental assessments issued in Québec over the last fifteen years. The following data banks were consulted for sources of data: Codoc, Elias, Aquaref, Georef, Biosis Previews, Envirodoq, Asfa, Water Resources Abstract and Zoological Resources. Documentation centres, government libraries and certain government services also provided articles, scientific publications and technical reports. Among the main sources of data in the bank are reports produced for the St. Lawrence Centre, the St. Lawrence River Study Committee, the Archipel Project and Hydro-Québec, and environmental assessment statements submitted to the Environment Canada's Environmental Assessment Branch and the Québec Department of the Environment.

Data on federal dredging activities come from Public Works Canada; this department is responsible for awarding contracts, for execution of dredging projects and for environmental assessments conducted for the federal government. The Québec Department of the Environment supplied data on dredging operations subject to section 31 of the *Environment Quality Act*, under which certain types of projects (among them dredging of areas larger than 5 000 m^2) are subject to an environmental impact assessment and review procedure.

2.2 Data selection and processing

The data that serve as reference for this report come from a status report prepared for the St. Lawrence River Study Committee by a group working under Jean-Baptiste Sérodes (Sérodes, 1978). The report gives findings of an exhaustive physicochemical survey of river sediment between Cornwall and Montmagny conducted between 1972 to 1976 by a variety of university and government agencies. The four main sediment fractions of about 850 surface sediment samples from as many sampling stations were analyzed for nine metals and metalloids, five nutrients and particle-size distribution.

To identify surface sediment contamination trends, more recent data from a variety of characterization programs were compared with the data published by Sérodes (1978). The following criteria were used to select pertinent sources of data from Dragsed:

- Samples had to be fairly recent (preferably since 1985).
- Samples had to be from the surface layer of sediment (0 - 5 cm).
- The entire sediment sample had to have been analyzed.
- Metal analysis had to include total digestion.

These selection criteria severely limited data that could be used for comparative analysis. The main data sources selected for the stretch of the St. Lawrence River between Cornwall and Pointe du Lac were Champoux et al. (1988), Hardy et al. (1991a and 1991b) and Lorrain et al. (1992a and 1992b).

For reaches downstream of Pointe du Lac, recent exhaustive characterization studies, studies of specific stretches of the river and all environmental assessments conducted for dredging projects also served as data sources.

Contamination trends of the following metals were analyzed and assessed: cadmium, chromium, copper, mercury, nickel, lead and zinc.

Tables and maps were prepared to present sediment quality data. The maps illustrate the following:

- Particle-size distribution
- Distribution of heavy metals studied (comparison)[1]
- Substances or groups of substances that exceed Toxic Effect Threshold (TET) quality criteria (as defined by the St. Lawrence Centre and the Québec Department of the Environment, 1992)

The software program SPANS was used to analyze spatial data for development of bathymetric and particle-size distribution maps. Particle-size distribution was mapped with SPANS' Potmap (Potential Mapping) module. A point file was used for analysis. A wide range of linear or exponential relations between points can be selected with this method (linear relations were chosen). A 500-m radius of influence was attributed to each point--except in the gulf, where a 2.5-km radius was selected. In addition, an average of the ten nearest stations was used for interpolation between stations. All surface sediment particle-size data available (0-10 cm) were used for map generation.

Oracle was used to correlate physicochemical data and sediment quality criteria, and Microstation was used to map contaminant distribution and exceedences of sediment quality criteria.

Descriptive statistics were calculated. The quality criteria established by the St. Lawrence Centre and the Québec Department of the Environment (1992) were used. These criteria are based on the relation between increases in contaminant concentrations and changes in the structure of the benthic community using the screening level

---

1. Sediment quality criteria established by the St. Lawrence Centre and the Quebec Department of the Environment were used in drafting metal distribution maps, even though the criteria were developed for extractable rather than total trace-metal fractions. There was no other choice given the lack of St. Lawrence River quality criteria for total fractions of the metals studied.

concentration approach.[2] Table 1 lists the quality criteria for the metals considered in this report.

Table 1 ***Interim quality criteria for St. Lawrence River sediment (St. Lawrence Centre and the Québec Department of the Environment, 1992)***

Metal (µg/g, dry weight)	No Effect Threshold (NET) (Level 1)	Minimal Effect Threshold (MET) (Level 2)	Toxic Effect Threshold (TET) (Level 3)
Extractable cadmium	0.2	0.9	3
Extractable chromium	55	55	100
Extractable copper	28	28	86
Total mercury	0.05	0.2	1
Extractable nickel	35	35	61
Extractable lead	23	42	170
Extractable zinc	100	150	540

It would have been better to use extractable rather than total metal fractions for this study, since only extractable fractions are bioavailable and hence liable to be detrimental to living organisms in the aquatic environment. In Lake St. Francis, extractable fractions constitute the major portions of total concentrations of copper (75 percent), lead (81 percent) and zinc (67 percent) (Lorrain et al., 1992a). Bioavailable fractions include metals that are exchangeable, metals bound to carbonates or to iron or manganese hydroxides, and oxidizable metals (that is those bound to sulphurs or organic

2. The quality criteria classify sediment in three management levels:
 - Level 1 or No Effect Threshold (NET): Background level, no chronic or acute effects
 - Level 2 or Minimal Effect Threshold (MET): Concentrations at which some effects are noticeable on some organisms, but which is tolerated by the majority
 - Level 3, Toxic Effect Threshold (TET): Concentrations with a harmful effect on most benthic organisms

matter). There were not enough data on measured concentrations of extractable fractions, however, to warrant their use for the study described herein.

3 AVAILABILITY OF HEAVY METALS IN SEDIMENT

Jaagumagi (1992) provides an excellent review of availability of heavy metals in sediment. The highlights of his study are outlined below.

3.1 Mercury

In aquatic systems, mercury is generally adsorbed to organic matter. Mercury can exist in three oxidation states: elemental, H^{9+} and Hg^{2+}. In natural waters at low redox potential, Hg^{2+} predominates. In anaerobic sediment, mercury can combine with sulphur to produce insoluble sulphides (Rudd et al., 1983). Both oxidized forms of mercury (Hg^{+} and Hg^{2+}) can be methylated by microorganisms under aerobic and anaerobic conditions. When pH is high and elemental mercury concentrations are low, the dimethyl form predominates. Under conditions of low pH and high concentrations of elemental mercury, the monomethyl form predominates. Both forms may also be demethylated by bacteria in sediment.

Rates of methylmercury production are strongly affected by oxygen. Methylated forms of mercury are usually the most bioavailable forms. Uptake of elemental mercury appears to be low, though plankton seems to accumulate this form of mercury more than other organisms (Rudd et al., 1983).

Bioaccumulation and bioconcentration of methylmercury is high. Since solubility and methylation rates increase at low pH, uptake can be higher under acidic conditions (CCREM, 1987).

3.2 Copper

Copper in aquatic systems can exist in four oxidation states; Cu^{+} et Cu^{2+} are the most common. Under aerobic conditions, Cu^{+} is readily oxidized to Cu^{2+}. In natural waters, copper undergoes complex reactions and can be present in solution as cupric ions or complexed with inorganic or organic ligands.

Copper is most often transported to sediment in association with organic matter and as precipitates of copper hydroxides, phosphates and sulphides. Copper in sediment has a high affinity for hydrous iron and manganese oxides, clays, carbonate materials and organic matter, though formation of these complexes is pH and redox dependent. With normal pH and inorganic carbon, copper is mainly present in the form of organic complexes, cupric carbonate complexes and coprecipitates with iron and manganese oxides (Brook & Moore, 1988; CCREM, 1987).

In reducing sediment, copper appears primarily in the form of sulphide complexes, and is thus immobilized in the sediment. In the oxidized zone, copper is mainly bound to organic matter or to hydrous iron and manganese oxides. Copper can be released from sediment through ion exchange, matrix solubilization (in the case of iron and manganese hydroxides) or matrix decomposition (in the case of organic matter).

Since copper is an essential micronutrient, it is readily accumulated by aquatic organisms (especially those lower down in the food chain), but there is no evidence of biomagnification. Some organisms can limit uptake of copper by increasing depuration rate (Luoma, 1983).

3.3 Zinc

Zinc occurs in aquatic systems as Zn^{2+}, which is amphoteric (capable of combining with acids as well as bases). It can also form organozinc compounds. At neutral pH, zinc is deposited in sediment through adsorption to hydrous iron and manganese oxides, clay minerals and organic matter. Below pH 6.0., adsorption is very low.

Zinc in the water column can be adsorbed to organic matter or coprecipitated with aluminium oxides or with iron or manganese oxides/hydroxides. In coarse sediment low in organic matter, zinc binds mainly with iron and manganese hydroxides. In fine-grained sediment, sorption to organic matter seems the most significant fate (Brook & Moore, 1988). In oxidized sediment, zinc forms the complexes mentioned. Under reducing conditions, zinc can be released to the water column or form insoluble sulphides (Moore et al., 1988).

Zinc can also exist as free ions in sediment pore water. Zinc in sediment pore water seems to be controlled by solubility of iron and manganese oxyhydroxides in the oxidized layer (particularly as these dissolve with the advent of reducing conditions) and by sulphides in the reduced layer.

Zinc is an essential micronutrient and uptake in most aquatic organisms appears to be independent of background concentrations. Zinc has been found to bioaccumulate in some organisms though there is no evidence of biomagnification.

3.4 Lead

Three lead oxidation states are of particular importance in aquatic systems; of these, Pb^{2+} is the most stable form. Transport of lead to sediment is mainly through coprecipitation with hydrous iron and manganese oxides, complexation with clays and sorption to organic matter. Much of the lead in sediment is found in association with iron and manganese hydroxides. In oxidized sediment, lead is strongly bound to hydroxides and organic matter. Under reducing conditions, lead can be released to the water column or can form sulphides as iron and manganese hydroxides dissolve.

Lead can bioaccumulate, mainly in the form of Pb^{2+} and its organic compounds (such as tetraethyllead). At low pH (about 6.0), organisms accumulate more lead than at higher pH, presumably because of greater availability of divalent lead at these pH levels.

3.5 Cadmium

In water, cadmium generally occurs in the Cd^{2+} form as a constituent of inorganic (halides, sulphides, oxides) and organic compounds (CCREM, 1987). Cadmium in the water column can exist as free ions or complexed to various ligands such as humic acids, organic particles and various oxides. Transport of cadmium to sediment occurs mainly through adsorption to organic matter and coprecipitation with iron, aluminium and manganese oxides. Cadmium can also be deposited in sediment through ion exchange, mainly with calcium.

Cadmium can also exist in sediment as free ions in sediment pore water as well as bound to other sediment fractions. Sediment pore water concentrations seem to be controlled by solubility of iron and manganese oxyhydroxides in the oxidized layer and by sulphides in the sulphide layer (Moore et al., 1988).

Cadmium in sediment can bioaccumulate. Bioavailability depends on pH, redox potential, water hardness and presence of other complexing agents. Uptake by biota appears to depend on availability of free ions (uptake through adsorption) and strength of binding to sediment solid phases (uptake through absorption). Studies suggest cadmium generally has a long residence time in biological tissue.

3.6 Chromium

In aquatic systems, chromium is present mainly in the Cr^{3+} (chromic compounds) and Cr^{4+} (chromate and dichromate) states (CCREM, 1987). The Cr^{4+} form is relatively soluble and is not adsorbed to any significant degree by particulate matter. In water, Cr^{4+} reacts strongly with oxidizable, usually organic, molecules with the resultant formation of Cr^{3+}. Cr^{3+} can be transported to sediment through adsorption to organic particles and coprecipitation with hydrous iron and manganese oxides. Under anaerobic conditions, Cr^{4+} is reduced to Cr^{3+}. Under anoxic conditions, chromium can form insoluble sulphides. Cr^{4+} is more readily bioaccumulated than Cr^{3+} and is considered the more toxic form. Tissue residue levels however are generally lower than sediment levels (CCREM, 1987). There is no evidence that chromium can biomagnify through the food chain.

3.7 Nickel

In aquatic systems, nickel occurs primarily in the Ni^{2+} form. In the water column, nickel occurs as relatively soluble salts that form a large number of complexes with organic material.

Nickel is deposited in sediment through coprecipitation with iron and manganese oxides and adsorption to organic matter. At neutral pH, nickel in sediment forms complexes with iron and manganese oxides. Under anaerobic conditions, nickel can form insoluble complexes with sulphides.

Nickel can be bioaccumulated by some organisms, though bioconcentration factors decrease from algae to fish (CCREM, 1987).

4 SEDIMENT QUALITY IN THE RIVER PROPER

4.1 Subsystem 1: Cornwall to the Beauharnois Canal outlet

4.1.1 Physiography and dynamics. This subsystem consists of Lake St. Francis and the three channels into which it flows at its outlet: the Beauharnois Canal, a man-made canal that receives most of the discharge; and two natural channels, the St. Charles River and the main stream of the St. Lawrence, which circle De Salaberry Island and then course through a series of rapids.

Lake St. Francis is an elongated depression in the St. Lawrence lowlands at elevation 46.5 m. The lake is 50 km long and nowhere more than 6 km wide. It forms a 233-km^2 reservoir that is partially controlled by the Beauharnois Dam in the Beauharnois Canal and by a series of dams at Coteau du Lac. Downstream, flow is regulated by the Cedars, Juillet Island, St. Timothée, Pointe du Buisson and Pointe des Cascades dams. Vertical drop is 25.2 m between Cornwall and the Beauharnois Canal outlet, a distance of about 75 km. Because of the regulation, water level fluctuates no more than 0.3 m (monthly average) over a year (Sloterdijk, 1985).

Figure 1 shows the bathymetry of Lake St. Francis. It is a shallow body of water--average depth is 6 m (Allen, 1986)--though it has three depressions more than 10 m deep, one of them 28 m deep. Upstream, deep narrow channels surround an archipelago. In the upstream third of the lake, a set of deep channels cross a series of shallows. In the centre of the lake, there is a moderately deep zone. The St. Lawrence Seaway runs through the lake. There are a few shallows in the central and downstream parts of the lake. There are also large shallow areas along the shores of the lake and in bays. The seaway runs west to east through the lake, sometimes closer to the north shore, sometimes closer to the south shore. Though guaranteed depth of the seaway is only 8.7 m, it runs through depressions more than 23 m deep in spots. Lake St. Francis does not require much maintenance dredging.

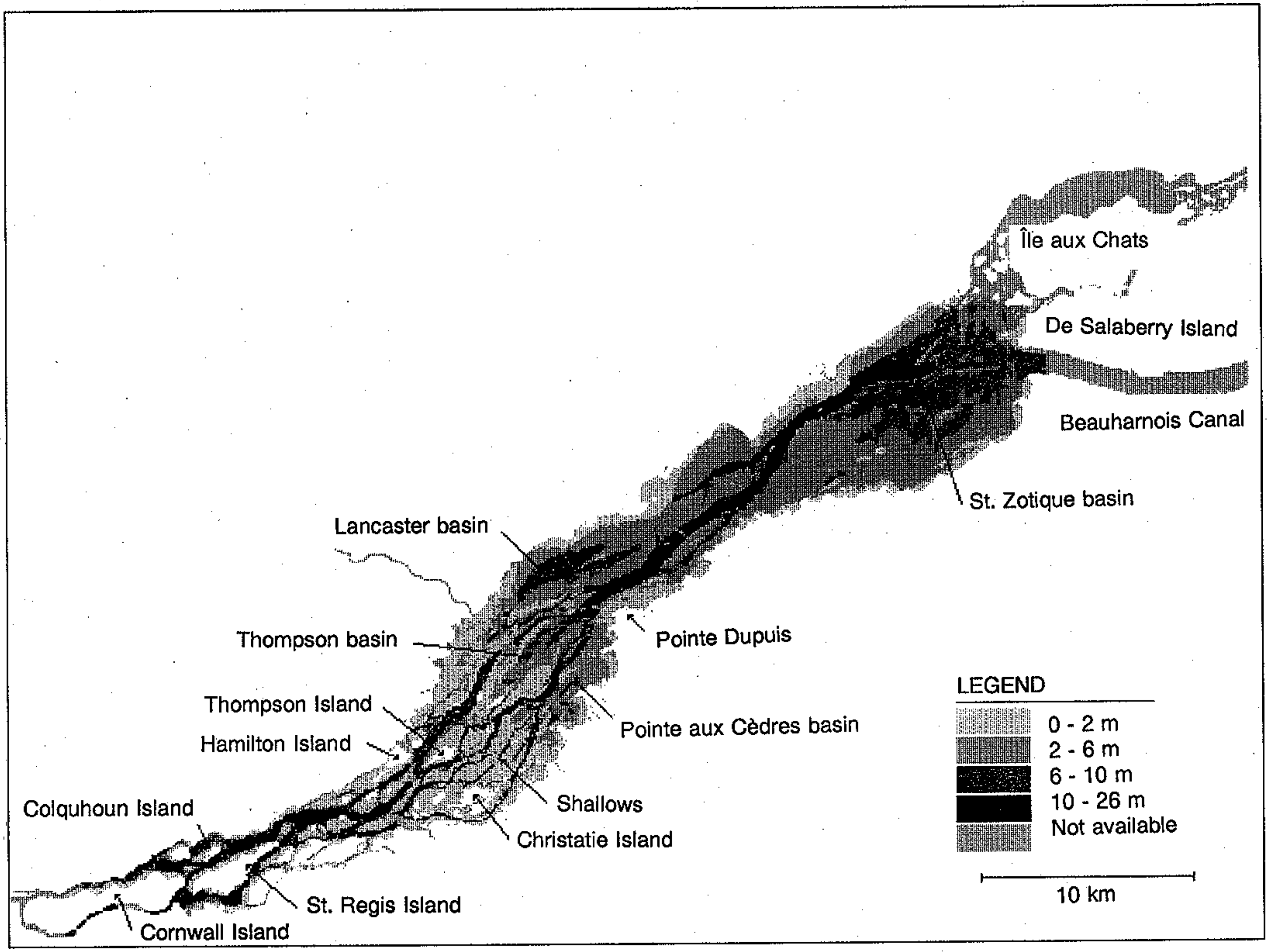


Figure 1 Bathymetry of Lake St. Francis

Mean annual discharge at Cornwall was 7 890 m^3/s between 1980 and 1989 (Table 2). Maximum mean annual discharge was 8 900 m^3/s (in 1986) and minimum mean discharge was 6 900 m^3/s (in 1989). Variations are minimal because of natural regulation by the Great Lakes and artificial regulation from dams sited in the international section of the St. Lawrence. Residence time is 32 hours in the main channels and 12 days in lateral channels (S. Lorrain, personal communication). The Beauharnois Canal receives more than 85 percent of the discharge from Lake St. Francis outlet (Hydrotech, 1989). Salmon River discharge is 12 m^3/s and Delisle River discharge is 6 m^3/s (Asseau, 1992a). Salmon River provides 67 percent of the total annual discharge of the two tributaries.

Table 2 Mean annual discharge of the St. Lawrence River at Cornwall between 1980 and 1989 (Asseau, 1992a)

Year	Mean annual discharge (m^3/s)
1980	7 850
1981	7 630
1982	7 650
1983	7 650
1984	7 990
1985	8 030
1986	8 900
1987	8 300
1988	7 000
1989	6 900
Mean (1980-89)	7 890

As for flow velocities, Lake St. Francis is a fairly dynamic water system; on the whole, fluvial rather than lacustrian conditions prevail (Sloterdijk, 1985). On the basis of the mathematical model developed by Sydor (1978) for a simulated flow of 9 100 m^3/s (flood flow), velocities range from 0.2 to 1.2 m/s but are generally less than 0.6 m/s. Where currents are strongest (between the islands at the lake entrance, in deep parts of the channels in the upstream third of the lake and in the seaway) sediment cannot accumulate. Very calm areas are found in the depressions in the lake. In shallows and along the shoreline, velocities depend on weedbed development: velocities are highest during spring flood (sediment is transported during this period) and slowest in August and September when the weedbeds are at the height of their growth (favouring sedimentation of suspended solids).

Solid input from the Great Lakes is about 250 000 to 500 000 t/a (average concentration is 1.2 mg/L) and is relatively constant because of streamflow regulation and the size of the Great Lakes. Input at Cornwall is estimated at 800 000 t/a or 2 to 4 mg/L--which is not much considering the flow of the St. Lawrence. Input from the north shore is estimated at 40 000 t/a and input from Salmon River at 70 000 t/a. Source of most of the solid input is still unknown. Solid input at the Lake St. Francis outlet is estimated at 2 300 000 t/a or 7 to 8 mg/L (Hydrotech, 1989).

Landsat TM digital image analysis provided valuable information on the behaviour of suspended solids at different times of the year. In June, suspended sediment crosses the lake and settles in the St. Zotique basin. In September, however, the sediment is trapped by weedbeds colonizing the shallows. Digital images show the barrier effect of the seaway: the seaway prevents transport of suspended sediment between the north and south shores of the lake.

4.1.2 Sources of contamination

Industrial discharges. Except at the downstream end of the subsystem, there are no major industrial developments or urban centres along its shores nor any tributaries. Dissolved contaminants and contaminants fixed in the particulate phase come from the Great Lakes, one of North America's most industrialized drainage basins, as well as from the international section of the St. Lawrence. The closest sources of contamination in the international corridor are as follows: in the Massena area, two aluminum plants (Reynolds Metal Co. and ALCOA) and one foundry (General Motors Corporation-Central Foundry Division (GM-CFD)); and in the Cornwall area, a paper mill (Domtar), a textile mill (Courtaulds Fibres), four chemical plants (ICI, Cornwall Chemicals, Stanchem, Courtaulds Films)--three of them still in operation (Courtaulds Films closed in 1989)--and effluents from the municipality of Cornwall (Lorrain et al., 1992b).

Among main contaminants from the Cornwall area, on the north shore, are mercury, zinc, lead, copper and PAHs. Main contaminants from the Massena area, on the south shore, are PCBs and possibly PAHs (Anderson and Biberhofer, 1988; Chan, 1980; Kauss et al., 1988). The Raquette and Grass rivers used to receive industrial discharges from the Massena area, and they are also highly contaminated by PCBs (Chan, 1980; Anonymous, 1982); these rivers may also play an active role in contaminating Lake St. Francis.

Lorrain et al. (1992b) report that the Massena GM-CFD plant began wastewater treatment in 1980 and that in 1988 the contaminated waste dump was covered to reduce rain wash of contaminated soil. Subsequent monitoring showed no PCB-contamination of storm runoff from the GM-CFD site. The ALCOA plant has been treating its wastewater since 1989 and the Reynolds plant since 1988.

The following information on local input comes from Asseau (1992a). Effluents from Expro Chemical Products Inc. and Canadian Electrolytic Zinc Ltd. discharge to Lake St. Francis outlets. Dominion Textile Inc. also discharged effluent to

Lake St. Francis outlets until the plant closed in 1992. In addition, there is a hazardous waste disposal site on Île aux Chats, at the Lake St. Francis outlet.

Dominion Textile Inc. operates an inorganic chemicals plant in St. Timothée. Before the plant closed, its effluent emptied into the Beauharnois Canal through a single outfall. Effluent from the plant was very alkaline (pH of about 9.5) until a neutralizing tank was installed in 1991. Mean annual discharge of the outfall was 0.0528 m^3/s.

Canadian Electrolytic Zinc Ltd. operates a plant in Valleyfield that manufactures zinc and cadmium ingots as well as copper cakes. It has two outfalls: a main outfall that discharges mainly cooling water (1.807 m^3/s), and a second combined outfall that discharges process water, domestic sewage and rain water (0.045 m^3/s). Both outfalls empty into the Beauharnois Canal.

Expro Chemical Products Inc. operates a chemicals plant in Valleyfield, close to the St. Charles River, that produces inorganic as well as organic chemicals--nitric acid, cyclonite, nitrocellulose, nitroglycerine and blasting powders. Wastewater is evacuated through some ten outfalls. Discharge from the two largest outfalls has been characterized; these outfalls discharge process water and rainwater to the St. Charles River, and their combined average discharge is 0.378 m^3/s.

Of the 16 parameters used to characterize liquid effluents in 1989, none proved common to the three plants. Table 3 shows reference metal loads measured at the three plants.

Table 3 ***Daily measured industrial metal (Zn and Cd) input to subsystem 1 (Asseau, 1992a)***

Metal	Dom. Tex.	Expro	CEZ
Zinc (kg/d)	--	--	99
Cadmium (kg/d)	--	--	0.6

Base years: 1988-1989
Inaccuracy of industrial loads: 30%
Expro: Expro Chemical Products Inc.
Dom. Tex.: Dominion Textile Inc.
CEZ: Canadian Electrolytic Zinc Ltd.
-- Not measured

CEZ, as the table shows, is notable for zinc input into the Beauharnois Canal. Another source of contamination that contributed until recently to deterioration of the quality of the environment around Îles aux Chats is Allied Chemicals; the Allied Chemicals plant was a factor in deterioration of the St. Charles River. Because of the geographic positions of the four plants discussed above, their effluents affect sediment quality only at subsystem 1 outlets.

Tributaries. Only very partial information is available about tributaries (Asseau, 1992a); there are data about only two of the seven tributaries of the subsystem--Salmon River, which empties into Lake St. Francis, and Delisle River, which empties into the St. Lawrence close to De Salaberry Island. Table 4 shows estimated loads of the two tributaries.

Input of these tributaries is negligible compared to that of other St. Lawrence tributaries further downstream (the Ottawa and St. Maurice rivers, among others). Tributary input is scarcely perceptible locally. Measured copper and lead contents of the Delisle River are below detection levels as are two of three zinc measurements. Loads of these contaminants cannot therefore be compared.

Table 4 Mean daily metal input (Cu, Zn and Pb) from the Salmon and Delisle rivers (Asseau, 1992a)

Metal	Salmon River	Delisle River
Copper (kg/d)	0.5	1.2*
Zinc (kg/d)	1.5	6.5
Lead (kg/d)	0.4	3.7*
Cadmium (kg/d)	0.05	0.5
Nickel (kg/d)	0.3	--

Base years: 1985-1987
Inaccuracy of tributary input: 45%
* Computed loads are overestimates since measured values are below detection limit
-- No data available

Municipalities. Table 5 shows municipal input to the subsystem. In 1989, 13 municipalities with a total population of more than 50 000 discharged wastewater to subsystem 1. More than half of this population (29 000 people) were residents of Salaberry de Valleyfield.

In 1989, municipalities discharged a daily load of about 1.6 kg of copper, 6.5 kg of zinc and 3.2 kg of lead to subsystem 1. Most of the load (84 percent) was discharged to the Beauharnois Canal and came from Valleyfield. The St. Charles River and the main stream of the St. Lawrence River, which run on either side of De Salaberry Island, receive wastewater from five municipalities with 25 percent of the area's inhabitants (13 000 people); this wastewater provides 9 percent of toxic input. Daily inputs of copper, zinc and lead were estimated at 0.21, 0.54 et 0.27 kg. Discharges from the seven Lake St. Francis municipalities, where about 18 percent of the subsystem's population lives (10 000 people), supplied 7 percent of total municipal input of the three reference metals; that is, 0.16 kg of copper, 0.40 kg of zinc and 0.20 kg of lead (Asseau, 1992a).

Table 5 ***Measured municipal metal (Cu, Zn and Pb) input to subsystem 1 (Asseau, 1992a)***

Municipality	Cu (kg/d)	Zn (kg/d)	Pb (kg/d)
Akwesasne	0.024	0.060	0.030
Dundee	0.006	0.015	0.007
Coteau Landing	0.024	0.060	0.030
Beaudette River	0.017	0.043	0.022
St. Zotique	0.034	0.084	0.042
St. Anicet	0.035	0.087	0.044
Ste. Barbe	0.020	0.049	0.024
Coteau du Lac	0.059	0.147	0.073
Grande Île	0.056	0.141	0.071
Les Cèdres	0.055	0.138	0.069
Pointe-des-Cascades	0.011	0.027	0.013
St. Timothée	0.034	0.086	0.043
Salaberry de Valleyfield	1.2	5.6	2.7
Total	1.6	6.5	3.2

Base year: 1989
Inaccuracy of municipal input: 50%

Municipal loads discharged to the subsystem are small compared to those discharged to the La Prairie basin and the Québec City area. They are, however, comparable to those discharged to Lake St. Louis. Loads discharged to the Beauharnois Canal can affect sediment quality locally.

Upstream St. Lawrence River reaches. Table 6 lists estimated input from upstream reaches of the St. Lawrence River based on water quality data recorded at Cornwall Island.

Table 6 Estimated daily metal (Cu, Zn, Pb, Cd, Cr and Ni) input at Cornwall Island (Asseau, 1992a)

Metal	Daily input (kg/d)
Cu	717.6
Zn	2 346.5
Pb	156.5
Cd	37.1
Cr	493.3
Ni	644.9

Base year: 1989
Minimum inaccuracy of input from upstream St. Lawrence River reaches: 25%.

Zinc tops the list with a daily input of about 2.3 t. At a station located 250 m from the north shore, zinc concentrations were as much as 20 times those recorded at other stations; this is attributable to local contamination. Next come copper, chromium, nickel, lead and cadmium, in that order. These metals are mainly transported via the seaway; metal load in the north channel is only 37 to 45 percent of total river load. Zinc and lead are exceptions to this rule however, since they come mainly from the north channel. Zinc and lead loads in the north channel account for about 50 percent of total zinc and lead loads. Note that hydraulic regime of the river was low in 1989 compared to 1986-1988 and 1990.

Summary. In 1989, 95 percent of estimated loads of the three reference metals (Cu, Zn and Pb) came from the Great Lakes and the Cornwall area (Table 7).

The other 5 percent derived from industrial plants, municipalities and tributaries. Tributary input has however been underestimated; five of the seven large tributaries could not be assessed for lack of data and even the data available for the other two were very incomplete. Industrial input may also have been underestimated since the reference metals were not measured in all effluents.

Table 7 Annual metal input (Cu, Zn and Pb) from the four main sources of contamination of subsystem 1 (Asseau, 1992a)

Source	Copper (kg/a)	Zinc (kg/a)	Lead (kg/a)	%
Industrial discharges	--	36 135	--	2.9
Tributaries	183	2 920	146	0.3
Municipalities	803	24 455	1 131	2.1
Upstream St. Lawrence River reaches*	261 908	856 487	57 115	94.7
TOTAL INPUT	262 894	919 997	58 392	100

Inaccuracy of industrial input: 30%
Inaccuracy of tributary input: 45%
Inaccuracy of municipal input: 50%
Inaccuracy of upstream St. Lawrence River reaches input: minimum 25%

* This source includes input from Massena and Cornwall.

To be precise, upstream reaches of the St. Lawrence River contribute close to 100 percent of total copper load, 93 percent of total zinc load and 98 percent of total lead load of subsystem 1. Municipalities contribute 0.3 percent of total copper load, 2.7 percent of total zinc load and 2 percent of total lead load. Tributary input of all three reference metals accounts for less than 1 percent of the total load of each metal. Industrial plants contribute close to 4 percent of zinc input; it is not known how much of the copper and lead loads derive from industrial effluents.

Table 8 gives the partial load data available for the other metals. The international section of the St. Lawrence transports significant quantities of cadmium, chromium and nickel to Lake St. Francis.

Table 8 Known metal input (Cd, Cr and Ni) to subsystem 1 (Asseau, 1992a)

Metal	Industrial plants	Tributaries*	Municipalities	Upstream St. Lawrence River reaches**	Total
Cd (kg/a)	--	18	--	13 542	13 560
Cr (kg/a)	--	--	--	180 096	180 096
Ni (kg/a)	--	1 095	--	235 402	236 497

Inaccuracy of industrial input: minimum 30%
Inaccuracy of tributary input: minimum 45%
Inaccuracy of municipal input: minimum 50%
Inaccuracy of input of upstream St. Lawrence River reaches: minimum 25%
* Lake St. Francis has a single tributary, Salmon River. The St. Lawrence River also has a single tributary in this area, Delisle River.
** This source includes input from Cornwall and Massena.
-- Not measured

4.1.3 Particle-size distribution. Sand dominates in most of Lake St. Francis, especially in the deep channels that cut longitudinally through the lake, circling the shallows and islands and forming the trough of the seaway (Figure 2). Sand also dominates in the central part of the lake and close to the Beauharnois Canal entrance and outlet (Table 9). Average velocities are higher in these sand-dominated areas than in other parts of the lake. Accumulated sand in the upstream part of the lake comes from the international section of the St. Lawrence. Sand in the centre of the lake comes from local sources, that is, moraine ridges and a border moraine close to Pointe Dupuis which have been disturbed (the disturbed material is transported by wave action) (Lorrain et al., 1992b).

Fine material dominates mainly in sheltered bays along both lakeshores as well as in the depressions in the central and downstream parts of the lake. In these areas, the flow section is much larger, and velocities are slower near the bottom as a result. Differences in particle-size distribution have been noted from one basin to the

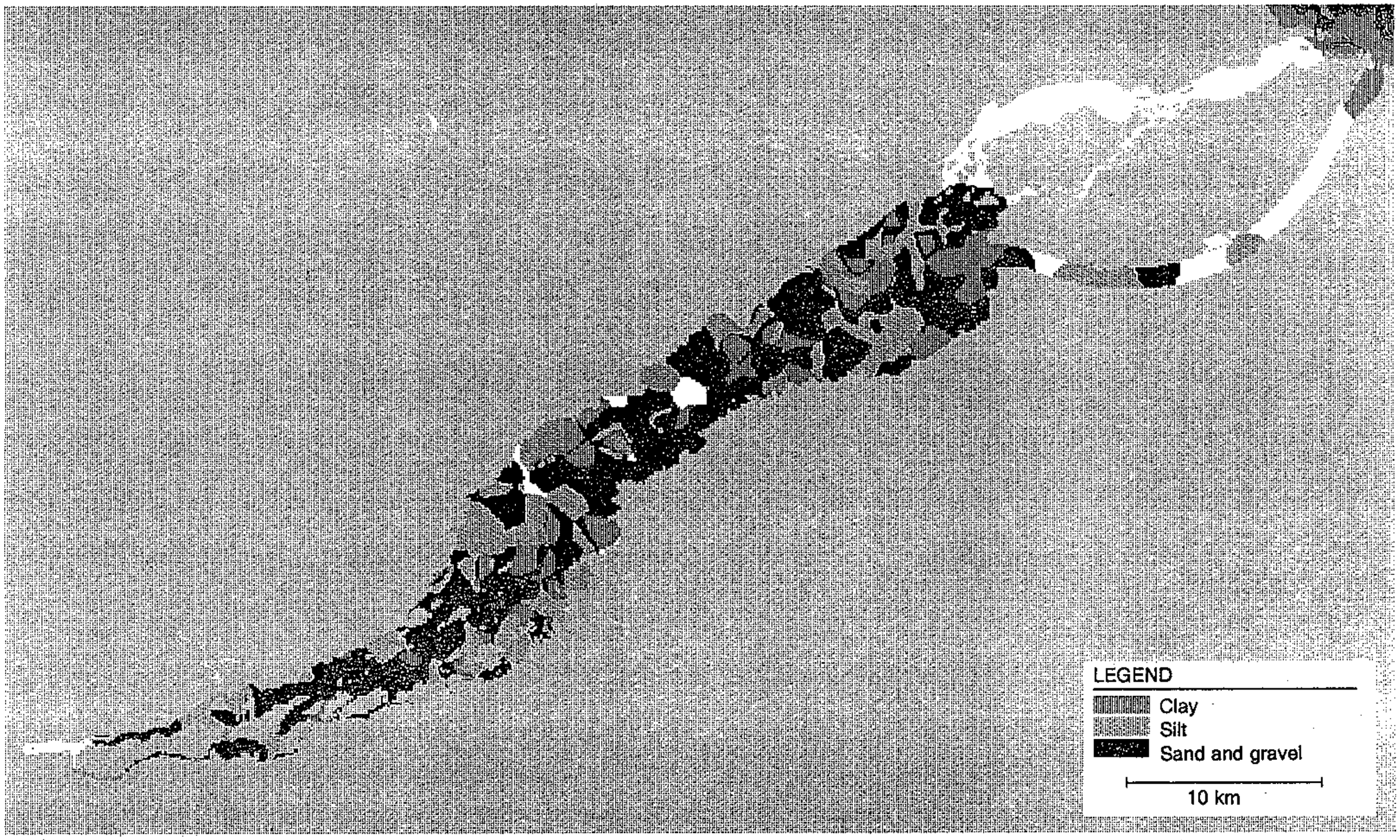


Figure 2 ***Dominant size fractions in Lake St. Francis***

Table 9 Dominant size fractions in subsystem 1

Area	Size class	Number of stations	Mean %	Standard deviation	Minimum %	Maximum %
Lake St. Francis	Clay	349	19	16	0	74
	Silt	349	31	22	0	92
	Sand	349	51	29	1	100
Cornwall	Clay	25	11	11	0	37
	Silt	25	36	21	0	80
	Sand	25	54	26	14	100
Massena	Clay	17	14	13	0	42
	Silt	17	28	19	0	56
	Sand	17	61	26	6	100
Raisin River	Clay	13	14	12	0	41
	Silt	13	31	25	0	72
	Sand	13	57	32	4	100
Pointe Dupuis	Clay	8	23	19	2	49
	Silt	8	27	16	9	50
	Sand	8	45	25	3	83
St. Zotique basin (northern part)	Clay	20	24	17	2	62
	Silt	20	32	18	2	63
	Sand	20	38	23	6	90
St. Zotique (southern part)	Clay	12	20	14	2	41
	Silt	12	36	20	12	65
	Sand	12	39	24	11	75
St. Zotique (upstream part)	Clay	8	26	16	2	46
	Silt	8	40	18	18	65
	Sand	8	32	20	11	67
St. Zotique (downstream part)	Clay	11	22	24	2	74
	Silt	11	23	13	6	47
	Sand	11	50	23	5	75
Thompson basin	Clay	1	0	0	0	0
	Silt	1	1	0	1	1
	Sand	1	99	0	99	99
Lancaster basin	Clay	2	26	23	10	42
	Silt	2	43	15	32	54
	Sand	2	26	30	5	47
Pointe aux Cèdres basin	Clay	7	31	23	0	52
	Silt	7	32	16	1	50
	Sand	7	44	30	12	99
Shallows	Clay	26	24	15	1	54
	Silt	26	33	20	0	63
	Sand	26	46	31	4	99
St. Charles River	Clay	6	41	46	0	33
	Silt	6	41	32	0	64
	Sand	6	18	15	4	100

next : substratum of the Thompson basin is sand, that of the Pointe aux Cèdres basin is muddy sand, that of Lancaster basin is sandy clay loam and that of the St. Zotique basin changes from sandy clay loam upstream to muddy sand downstream.

Substratum of the shallows is a mix of sand and fine sediment. The shallows are a temporary sink for fine material, which accumulates when weedbeds are at the peak of their growth (August to September) and is transported from the shallows during the following spring flood when the weedbeds have disappeared. The shallows are therefore not very favourable to permanent accumulation of sediment (Lorrain et al., 1992a and b). The central part of the lake, downstream of the shallows, is dominated by sand. This area is a fine materials transport zone; high velocities prevent deposition.

In other words, hydrological conditions in most of Lake St. Francis allow sand but not fine material to be retained. Fine material does accumulate temporarily in shallows when weedbeds are sufficiently well developed to slow down flow velocities. It also accumulates permanently along parts of the lakeshore and in some depressions. Accumulation rates have been estimated at 2.2 $kg/m^2/a$ in a secondary channel in the lake centre and at 1.2 to 8.0 $kg/m^2/a$ in a trough in the downstream part of the lake. Overall accumulation rate for the lake has been estimated at 3.5 $kg/m^2/a$ (Carignan et al., 1993).

Substratum in the upstream part of the St. Charles River is composed of clayey silt. Downstream, however, sand is the dominant fraction. There is very little information available about particle-size distribution in the Beauharnois Canal.

4.1.4 Physical chemistry. Lake St. Francis surface sediment has been known to be contaminated by heavy metals since the work of Centreau (Centreau, 1973, 1974, 1975). Sérodes (1978) discovered the north side of the lake and the St. Charles River were contaminated by mercury, copper, zinc, lead and chromium. The most contaminated parts of the lake were immediately downstream of Cornwall and the northern part of the St. Zotique basin (Figure 3). Relatively high concentrations of some metals (between TET and MET quality criteria) were also found south of Cornwall Island

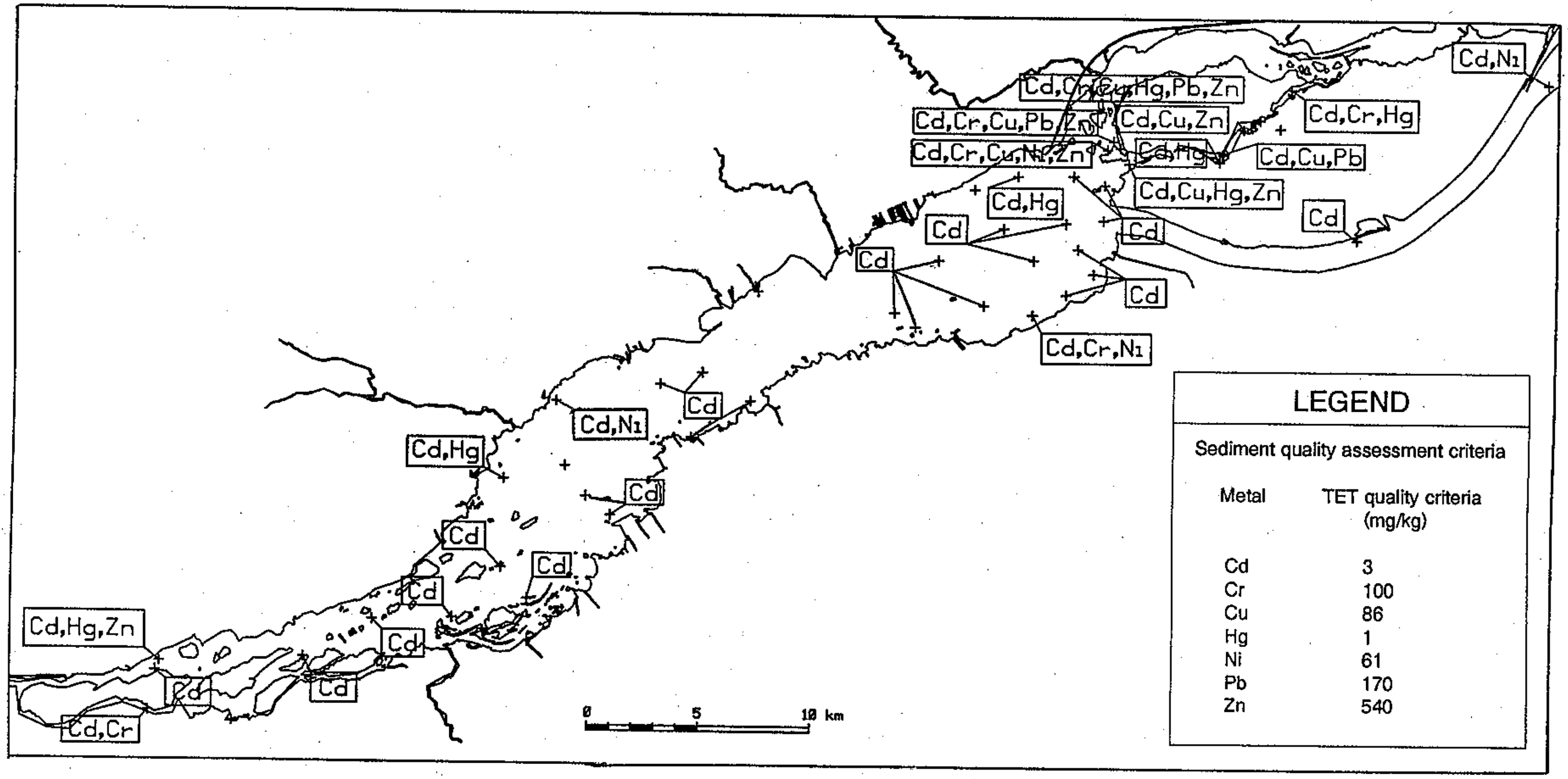


Figure 3 ***Exceedences of TET quality criteria in Lake St. Francis (1976)***

(downstream of Massena), in the shallows of the upstream third of the lake (downstream of Thompson Island) and in the Lancaster basin (Table 10). Lowest concentrations were in the centre of the lake, where levels were generally natural background. Quality index was higher on the north than the south shore.

Table 10   Subsystem 1 sediment quality statistics (1976 and 1989)

Year	Metal	No. of samples	% samples below detection level	Mean (µg/g)	Standard deviation (µg/g)	Median (µg/g)	Minimum (µg/g)	Maximum (µg/g)
1976*	Pb	80	0	47.34	89.45	18.00	0.00	560.00
	Cd	80	0	8.45	7.94	7.00	2.00	55.00
	Zn	80	0	298.02	737.91	133.00	15.10	6210.00
	Hg	80	1	1.10	2.46	0.19	0.00	10.15
	Ni	80	0	35.72	19.35	33.80	4.50	81.20
	Cu	80	0	65.08	114.97	36.90	4.25	742.00
	Cr	80	0	92.17	138.63	64.10	11.30	1050.00
1989**	Pb	65	2	25.41	12.63	24.20	0.60	54.90
	Cd	66	94	1.27	0.31	1.00	1.00	1.70
	Zn	66	0	154.73	105.55	125.00	18.00	452.00
	Hg	66	6	0.20	0.17	0.13	0.01	0.66
	Ni	66	0	21.29	9.58	20.60	3.70	45.50
	Cu	66	0	25.35	14.79	25.30	1.30	64.80
	Cr	66	0	38.30	15.03	35.00	11.00	83.00

* Sérodes J.B. (1978)
** Lorrain, S. and V. Jarry (1992a)

Median mercury concentration for subsystem 1 was 0.2 µg/g. Maximum mercury concentration was 10.2 µg/g. Highest concentrations were found in the upstream part of the lake downstream of Cornwall (2.9 µg/g), at the mouth of the lake, in the northern part of the St. Zotique basin (1.6 µg/g) and in the St. Charles River (12.42 µg/g) (tables 11 and 12). At these spots, mercury levels exceeded TET quality criterion (Figure 4).

Table 11 ***Median metal concentrations in seven zones of subsystem 1 (μg/g)***

Year	Metal	Cornwall	Massena	Raisin River	Pointe St. Louis	St. Zotique basin (northern part)	St. Zotique basin (southern part)	St. Charles River	Shallows	Lancaster basin
		Median	Median	Median	Median	Median	Median	Median	Median	Median
1976	Pb	63.00	0.00	0.00	5.00	53.00	25.00	230.00	28.00	6.00
	Cd	8.00	2.00	9.00	3.00	9.00	7.00	7.00	8.00	4.00
	Zn	177.00	25.80	101.00	44.40	281.00	148.00	419.00	126.00	67.90
	Hg	0.43	0.01	0.01	0.06	0.55	0.26	1.14	0.07	0.13
	Ni	36.70	4.50	61.00	11.80	38.20	29.30	43.70	31.20	17.20
	Cu	66.10	5.58	49.30	12.40	62.60	35.90	208.00	40.20	12.40
	Cr	73.40	22.50	97.10	32.20	73.90	60.00	111.00	50.70	33.20
1989	Pb	39.90	12.00	--	22.40	34.20	26.30	--	33.20	23.30
	Cd	1.00	1.00	--	1.00	1.00	1.00	--	1.00	0.00
	Zn	136.00	58.00	--	93.00	200.00	114.00	--	156.00	211.00
	Hg	0.22	0.05	--	0.09	0.30	0.15	--	0.16	0.30
	Ni	28.90	10.30	--	20.70	31.20	21.20	--	26.60	15.50
	Cu	38.40	7.80	--	18.30	36.80	25.30	--	35.50	25.60
	Cr	48.00	32.00	--	29.00	45.00	30.00	--	43.00	26.00

-- No data available

Table 12 Maximum metal concentrations in seven zones of subsystem 1 (µg/g)

Year	Metal	Cornwall	Massena	Raisin River	Pointe St. Louis	St. Zotique basin (northern part)	St. Zotique basin (southern part)	St. Charles River	Shallows	Lancaster Basin
		MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM
1976	Pb	110.00	46.00	0.00	5.00	315.00	45.00	560.00	43.00	6.00
	Cd	9.00	6.00	9.00	3.00	55.00	8.00	13.00	9.00	4.00
	Zn	648.00	251.00	101.00	44.40	6210.00	190.00	965.00	154.00	67.90
	Hg	2.87	0.59	0.01	0.06	1.63	0.62	10.15	0.25	0.13
	Ni	41.40	56.10	61.00	11.80	71.20	38.60	56.10	38.70	17.20
	Cu	80.50	30.00	49.30	12.40	742.00	54.40	324.00	40.50	12.40
	Cr	75.30	122.00	97.10	32.20	464.00	79.60	1050.00	56.30	33.20
1989	Pb	44.20	53.00	--	37.30	35.50	43.10	--	54.90	46.70
	Cd	1.10	1.00	--	1.00	1.00	1.00	--	1.70	0.00
	Zn	403.00	309.00	--	309.00	270.00	180.00	--	294.00	397.00
	Hg	0.64	0.19	--	0.39	0.36	0.23	--	0.38	0.66
	Ni	33.50	28.30	--	34.50	34.10	30.90	--	45.50	37.70
	Cu	44.90	33.40	--	43.40	41.70	38.40	--	64.80	54.70
	Cr	56.00	59.00	--	43.00	48.00	40.00	--	65.00	72.00

-- No data available

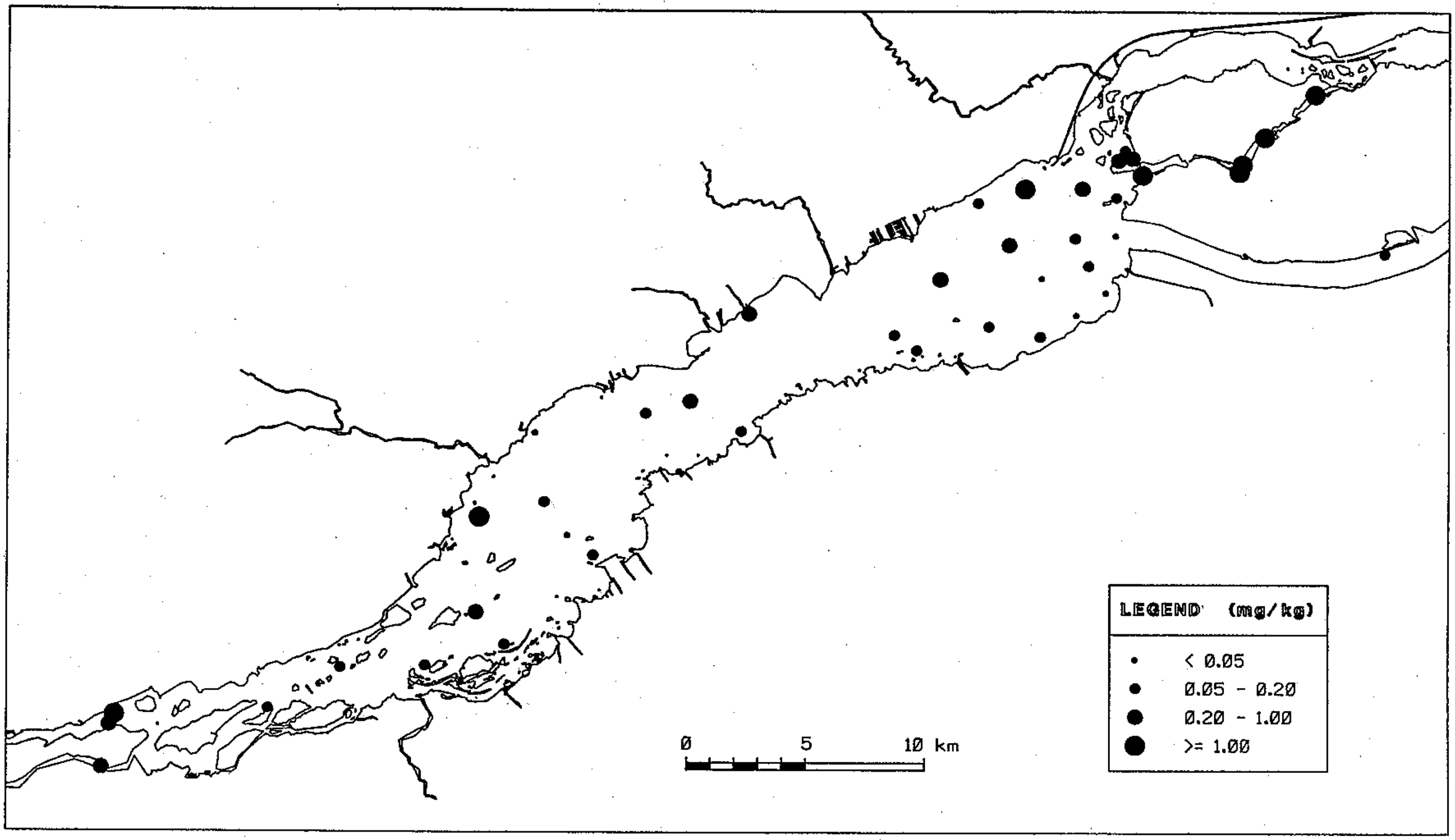


Figure 4 ***Mercury distribution in Lake St. Francis sediment (1976)***

Median was higher on the north side of the lake (0.22 μg/g) than on the south side (0.09 μg/g), confirming the northern part of the lake is more contaminated than the southern part. This information, together with knowledge of the discharges from Cornwall and of sediment quality near outfalls, suggests discharges from industrial plants in the Cornwall region affect sediment quality along the north shore of Lake St. Francis for a considerable distance. The higher concentrations in the downstream part of the lake may derive from local sources or from sedimentation in the St. Zotique basin. The high concentrations in the St. Charles River derive from local sources.

In 1976, distribution pattern of copper differed from that of mercury. The only area that was highly contaminated by copper in 1976 was a large area along the shores of Île aux Chats, at the lake outlet, that continues into the St. Charles River; here concentrations (maximum was 742 μg/g) were far above TET quality criterion (86 μg/g) (Figure 5). Median concentration in the subsystem was 36.9 μg/g, suggesting moderate anthropogenic input. Concentrations differed on the north and south sides (medians were 47.9 and 25.4 μg/g respectively), but medians upstream and downstream (30.0 and 36.9 μg/g respectively) were similar. Concentrations on the south side were natural background levels; on the north side and in the St. Zotique basin, concentrations moderately above background levels were noted.

Median concentration of zinc in subsystem 1 was 133 μg/g in 1976; values ranged from 15.1 to 6 210 μg/g. Main contaminated areas were immediately downstream of Cornwall (648 μg/g), along the shores of Île aux Chats (6210 μg/g) and in the St. Charles River (965 μg/g) (Figure 6). Moderately high concentrations of zinc--between MET and TET quality criteria (150 and 540 μg/g)--were detected in areas on the north side of the lake where severe or moderate mercury contamination was also detected (as mentioned earlier) : the shallows downstream of Thompson Island, the Lancaster basin and the northern part of the St. Zotique basin. In 1976, concentrations were higher on the north side of Lake St. Francis than on the south side (177 μg/g vs 82.1 μg/g).

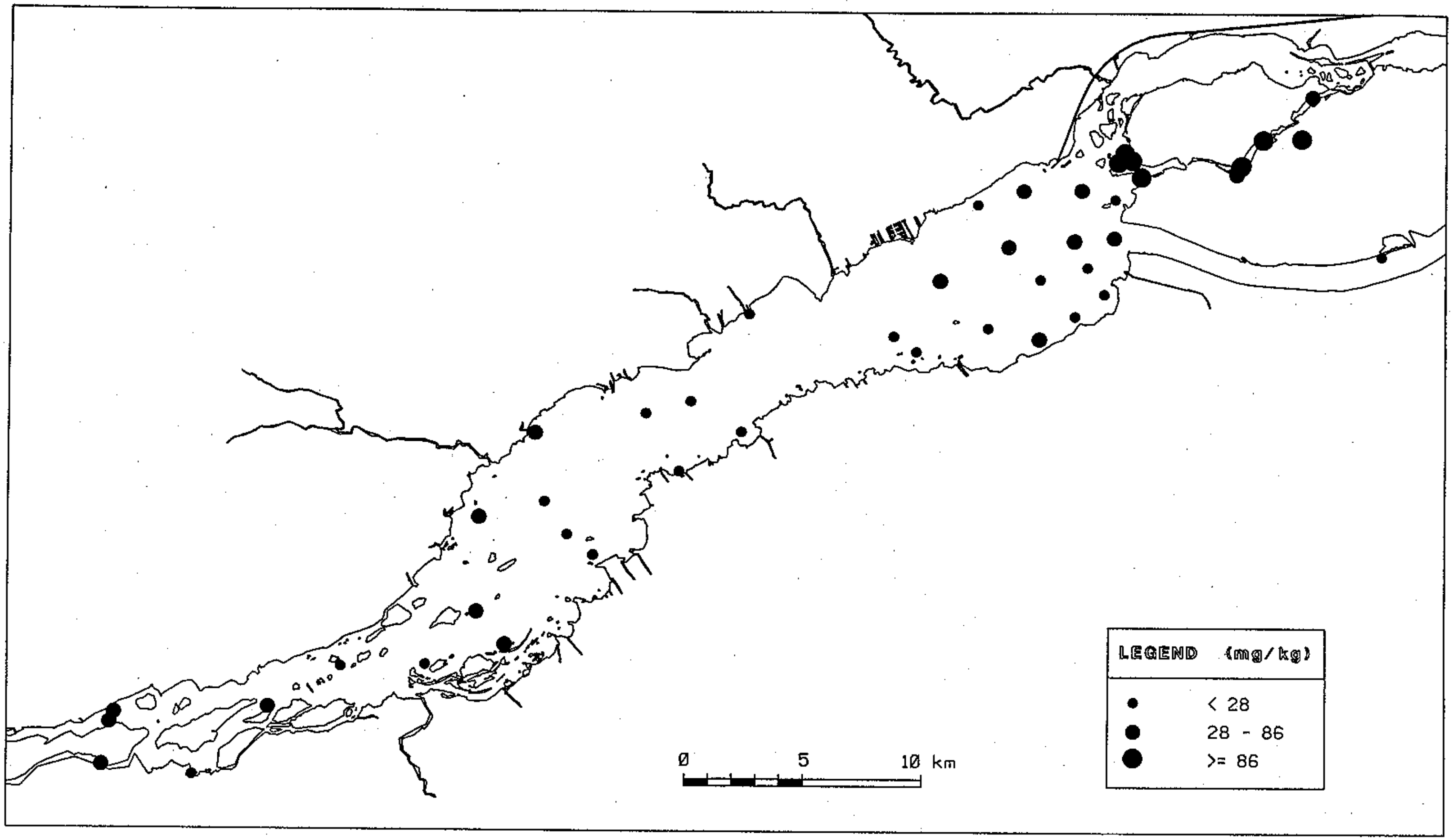


Figure 5 ***Copper distribution in Lake St. Francis sediment (1976)***

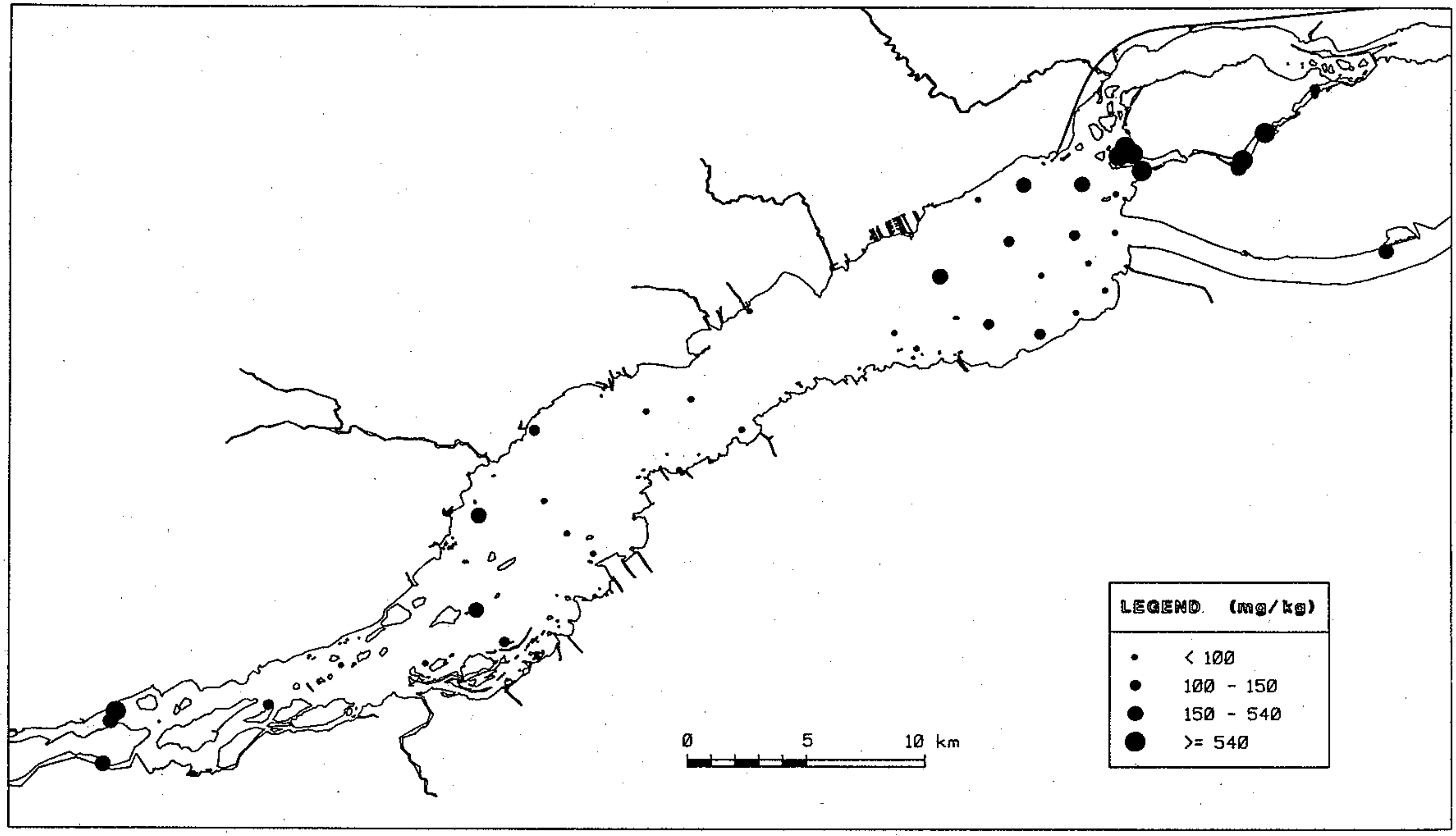


Figure 6 ***Zinc distribution in Lake St. Francis sediment (1976)***

Median lead concentration in subsystem 1 was 18 µg/g; lead content ranged from 0 to 560 µg/g. The main contaminated area was the St. Charles River (maximum 560 µg/g) (Figure 7). Other moderately contaminated areas were also identified (the same areas where high mercury concentrations were detected): downstream of Cornwall (110 µg/g), the northern part of the St. Zotique basin (315 µg/g) and the shallows downstream of Thompson Island (43 µg/g) (Figure 7). Average lead concentration was significantly higher in the northern part of the subsystem than in the southern part (36 µg/g vs 11 µg/g).

Median concentration of cadmium was 7 µg/g in 1976, a level liable to significantly impair benthic fauna. Concentrations ranged from 2 to 55 µg/g--indicating general cadmium contamination of subsystem 1--with particularly high concentrations in the Île aux Chats area (55 µg/g) (Figure 8).

Median concentration of chromium was 64.1 µg/g in 1976, indicating the entire subsystem is moderately contaminated by chromium. Concentrations ranged from 11.3 to 1050 µg/g. Highest concentrations were detected downstream of Massena (122 µg/g), along the shores of Île aux Chats (464 µg/g) and especially in the St. Charles River (1 050 µg/g) (Figure 9). Chromium distribution pattern resembled that of zinc.

Median concentration of nickel was 33.8 µg/g in 1976; concentrations ranged from 4.5 to 81.2 µg/g. Areas where concentrations matched or exceeded TET quality criterion (61 µg/g) were on the shores of Île aux Chats (71.2 µg/g) and at the mouth of Raisin River (61 µg/g) (Figure 10).

Observations by Sloterdijk (1985) in 1979-81 confirmed the major spatial variation in total mercury distribution in surface sediment of the subsystem. Sloterdijk detected high mercury concentrations (up to 1.5 µg/g) along the north shore, with greatest contamination immediately downstream of Cornwall. Sediment quality criteria were exceeded in many places. The contamination derived from point sources of mercury in Cornwall, sources which have been strictly regulated since 1972. Contaminated sediment are transported along the north shore from Cornwall and do not move across the lake

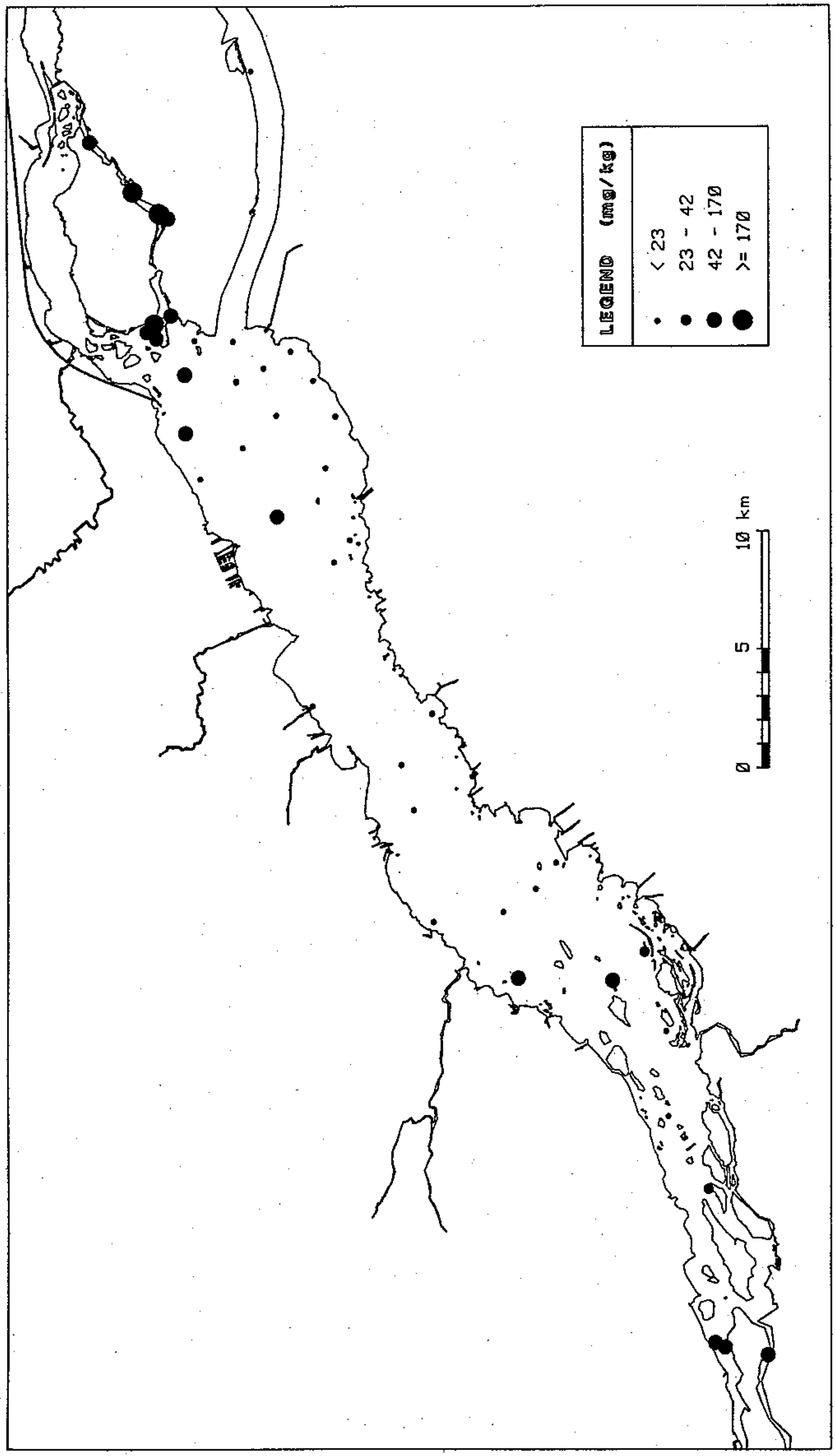


Figure 7 Lead distribution in Lake St. Francis sediment (1976)

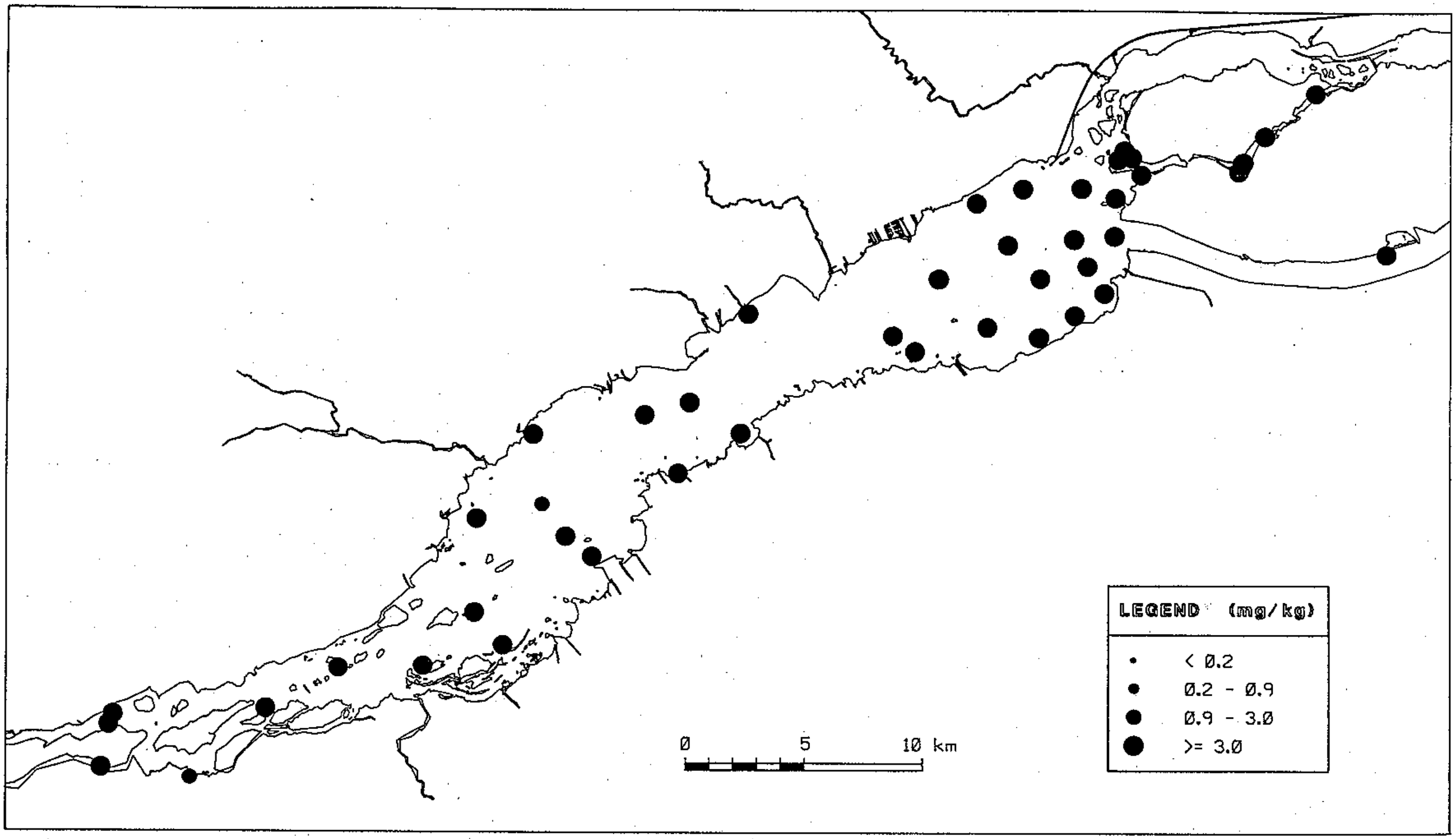


Figure 8 **Cadmium distribution in Lake St. Francis sediment (1976)**

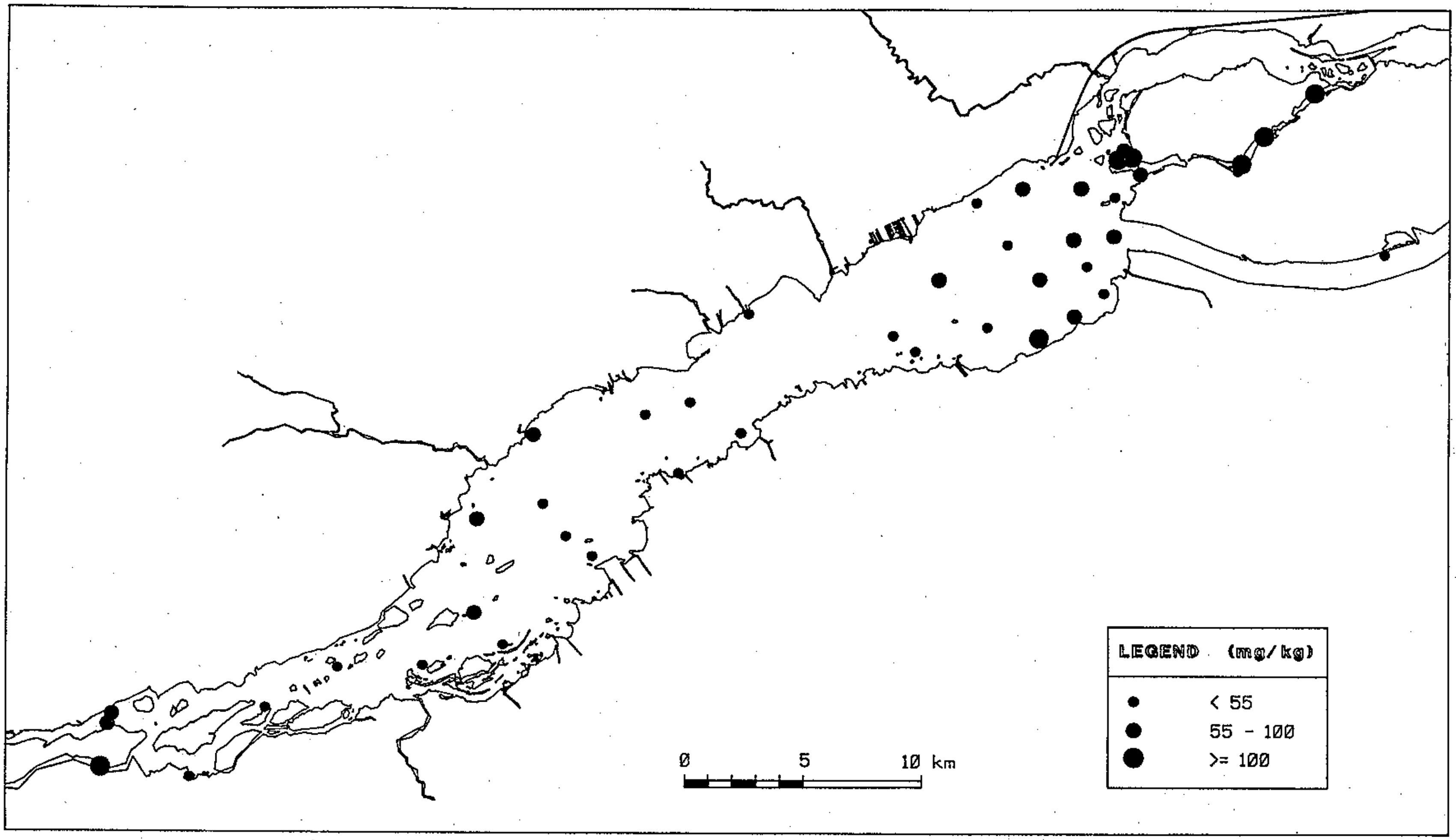


Figure 9 Chromium distribution in Lake St. Francis sediment (1976)

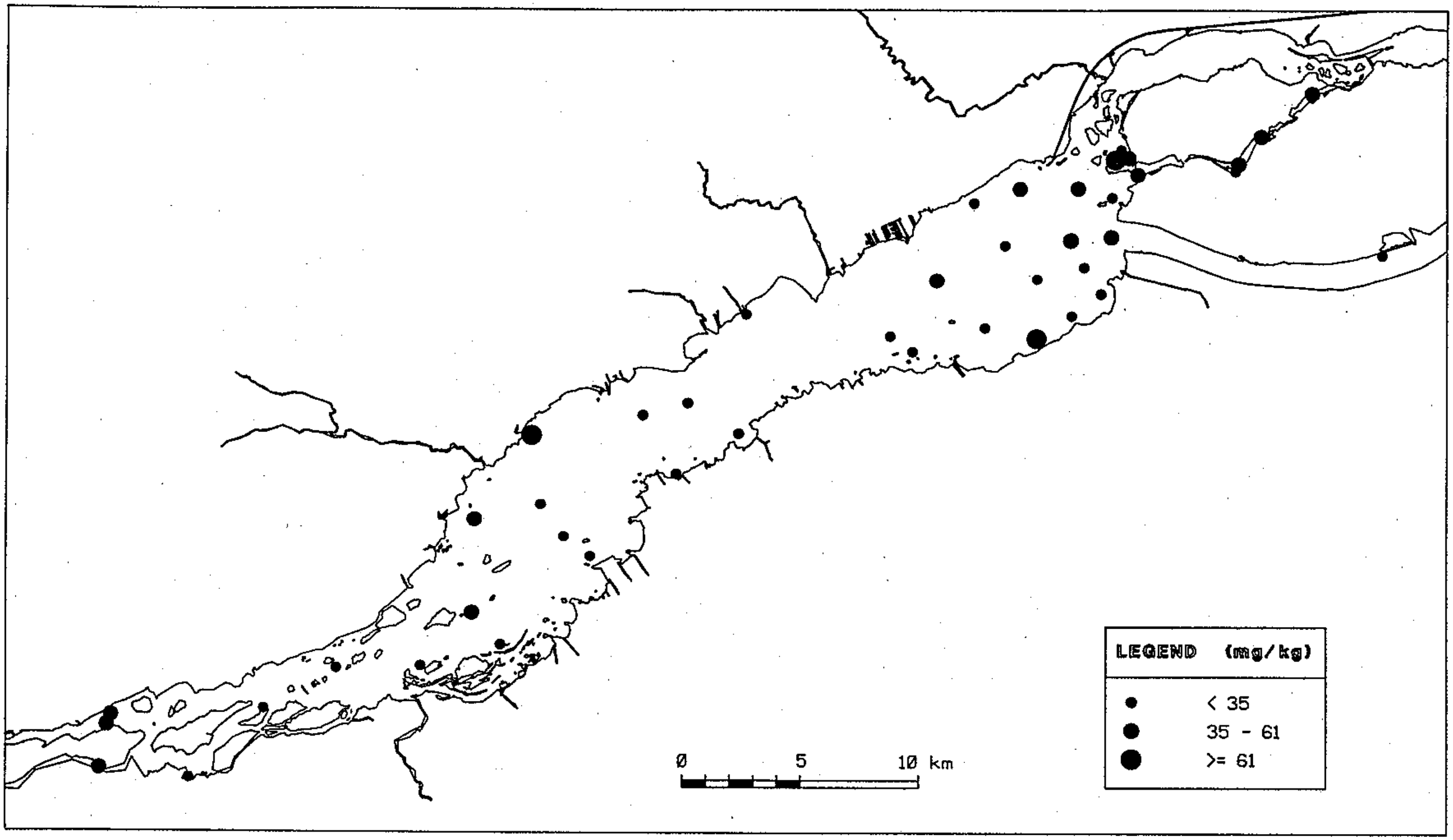


Figure 10 ***Nickel distribution in Lake St. Francis sediment (1976)***

towards the south shore. This is the case everywhere along the river corridor until the Richelieu rapids. A status report on sediment contamination of the Cornwall area confirmed that concentrations of all inorganic contaminants except iron are higher in the north channel of Cornwall Island (SLRT, 1991). Median mercury concentration in 1979-1981 for the lake as a whole was 0.3 µg/g.

Lorrain (Lorrain et al., 1992b) noted that total mercury concentrations along the north shore of Lake St. Francis were significantly lower (34 percent) in 1989 than in 1979-1981. In 1989, highest mercury concentrations were detected north of the seaway in the upstream part of the lake (0.64 µg/g downstream of Cornwall close to Pilon and Colquhoun islands; and 0.61 µg/g between Clark and Hamilton islands), in the two basins along the north shore (0.66 µg/g in the Lancaster basin and 0.36 µg/g in the St. Zotique basin) and in the shallows of the upstream third of the lake (0.38 µg/g) (Figure 11). In 1989, mercury concentrations exceeding TET sediment quality criterion (1 µg/g)--that is, the level at which there is a major impact on the environment--were no longer detected. The decrease in mercury contamination is attributable to a reduction in discharges to the Cornwall area following enforcement of regulations on industrial wastewater and demonstrates the major role of Cornwall area industrial plants in contaminating the northern part of Lake St. Francis.

Lorrain (Lorrain et al., 1992b) did not note a similar drop in concentrations on the south side; surface sediment concentrations had on the whole been below MET quality criterion here in 1979 (0.2 µg/g) and were still low in 1989. In 1989, highest concentrations on the south side (0.09 to 0.23 µg/g) were detected south of Cornwall and St. Regis islands, close to Christatie Island, in the shallows and in the southern part of the St. Zotique basin. These findings indicate there is little mixing of the water masses of the south and north sides of the lake and that there was no change in mercury input from the Great Lakes and the international section of the St. Lawrence River during the period. In 1989, median mercury concentrations in sediment in Lake St. Francis as a whole was 0.13 µg/g, with values ranging from 0.01 to 0.66 µg/g.

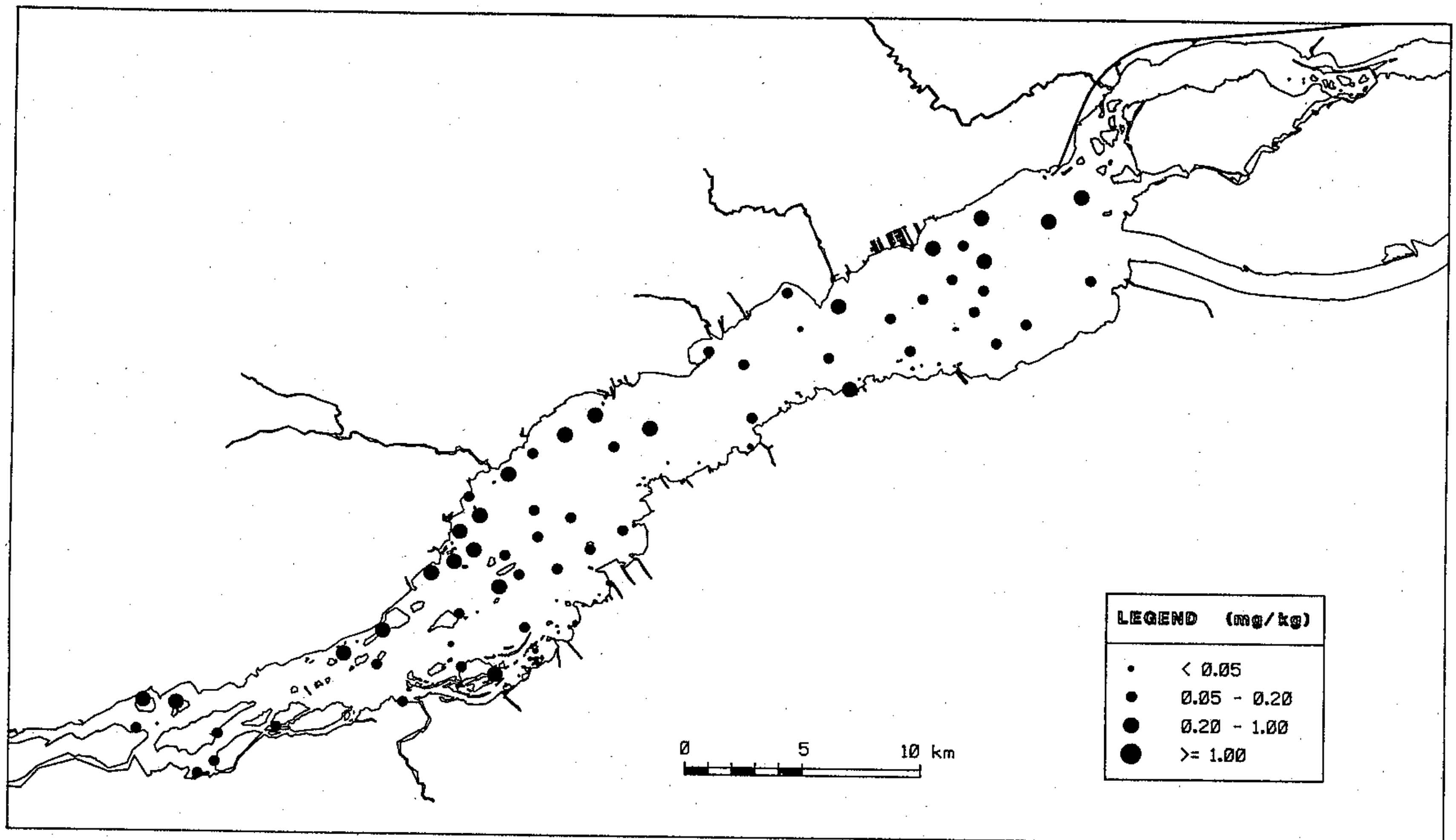


Figure 11 **Mercury distribution in Lake St. Francis sediment (1989)**

A similar decrease in concentrations relative to the previous decade was noted for the other heavy metals as well; concentrations no longer exceeded TET quality criteria. Median concentrations on the north side remained higher than those on the south side, and in some areas (downstream of Cornwall, at the mouth of Raisin River, along the shallows of the upstream third of the lake and in the St. Zotique basin) concentrations of certain contaminants exceeded average lake concentrations. On the whole, however, in 1989 there were no longer areas where heavy metal concentrations exceeded TET.

Median copper concentration was background level in 1989--25.3 μg/g compared to 36.9 μg/g in 1976. Concentrations ranged from 1.3 to 64.8 μg/g (compared to the maximum 742 μg/g recorded in 1976). There were still significant differences between the north and south sides of the lake: concentrations were higher on the north side (median of 33.9 μg/g vs 18.3 μg/g), suggesting significant input from Cornwall. Areas most contaminated by copper in 1989 were downstream of Massena, the St. Zotique basin and the shallows of the upstream third of the lake (Figure 12). For lack of data, however, it was not possible to determine whether the area encompassing Île aux Chats and the St. Charles River was still highly contaminated.

Median concentrations of zinc in 1989 and 1976 were comparable (125 μg/g in 1989 and 133 μg/g in 1976). Maximum concentrations differed significantly however (452 μg/g in 1989 compared to 6 210 μg/g in 1976). A significant difference was also noted between concentrations detected on the north side and those detected on the south side of the lake: the north side was more contaminated, and in some areas on the south side which were not sampled in 1976 moderately high zinc contamination was discovered--in the shallows downstream of Christatie Island, in the bay between Pointe Leblanc and Pointe au Cèdre and in the Pointe St. Louis bay (Figure 13). The area immediately downstream of Cornwall showed signs of improvement (median was 136 μg/g in 1989 compared to 177 μg/g in 1976; maximum was 403 μg/g in 1989 compared to 648 μg/g in 1976). In 1989, the most highly contaminated areas were the Lancaster and

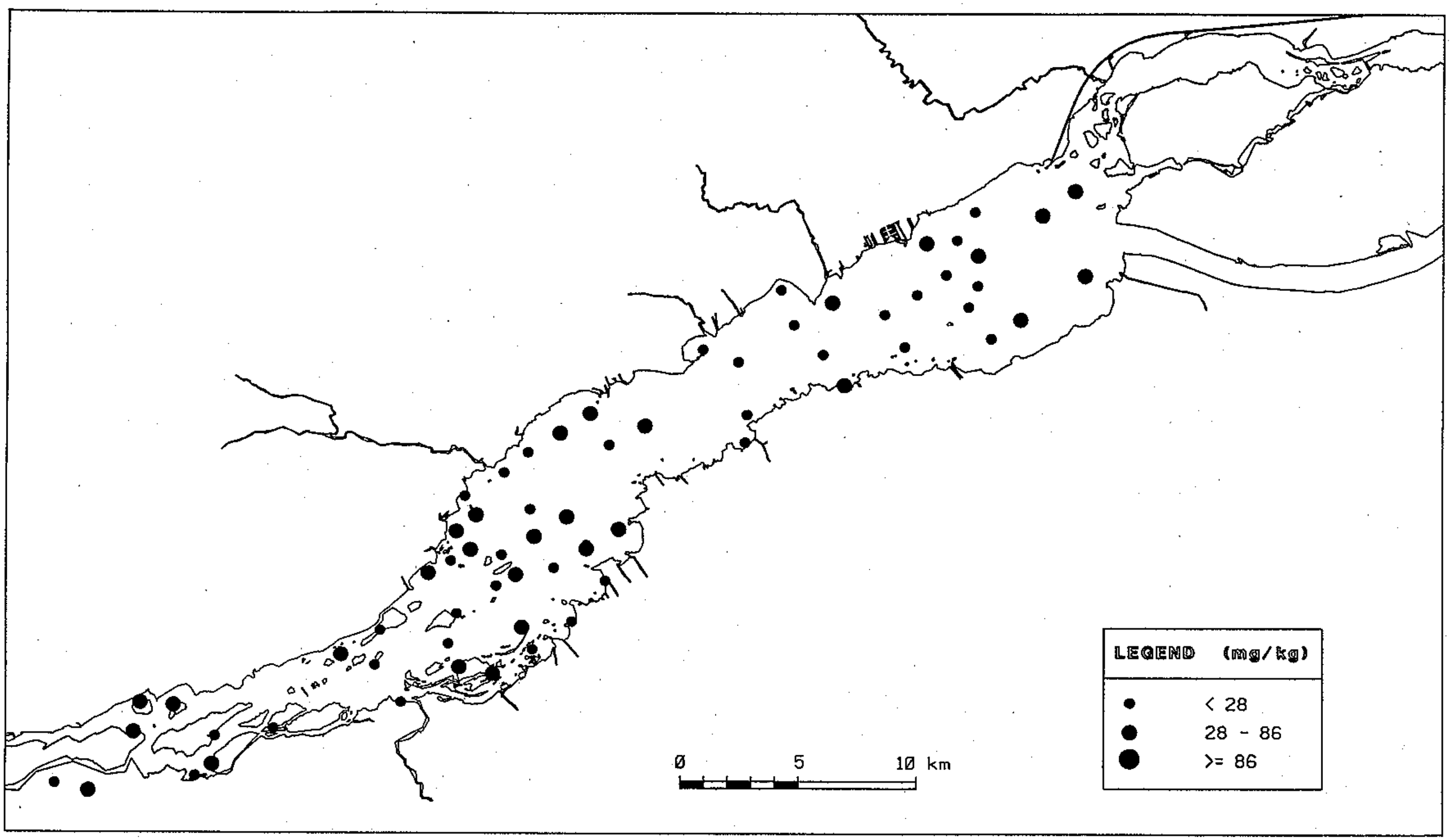


Figure 12 ***Copper distribution in Lake St. Francis sediment (1989)***

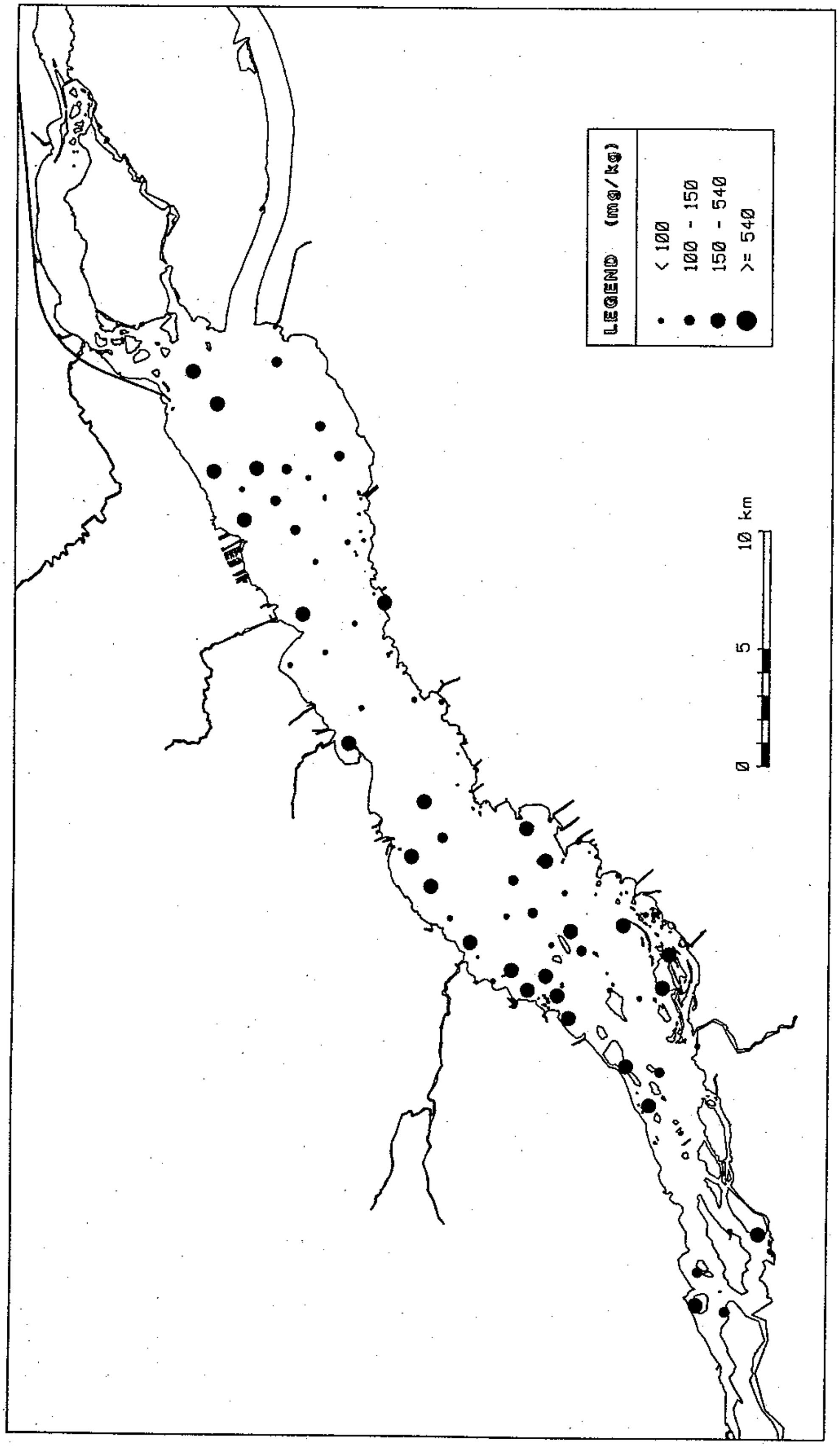


Figure 13 Zinc distribution in Lake St. Francis sediment (1989)

St. Zotique basins and the shallows of the upstream third of the lake. It was not possible to determine how the contamination detected in 1976 in the area encompassing the St. Charles River and the vicinity of Île aux Chats had developed, since it was not sampled in 1989.

The picture improved for lead as well compared to 1976. Though median concentration remained stable (24.7 μg/g compared to 18 μg/g in 1976), all values were below 55 μg/g in 1989--compared to 110 μg/g downstream of Cornwall, 315 μg/g in the northern part of the St. Zotique basin and a maximum 560 μg/g in the St. Charles River in 1976. In other words, in the space of the decade, surface sediment quality improved downstream of Cornwall and in the St. Zotique basin and remained stable in other areas. Lead contamination was still however greater downstream of Cornwall and in the St. Zotique basin than anywhere else in Lake St. Francis (Figure 14). In 1989, no significant differences in lead concentrations on the north and south sides of the lake were detected.

Median concentration of cadmium was 1 μg/g in 1989 compared to 7 μg/g in 1976. Figure 15 shows data collected. Because so few values (n = 4) were used to calculate the median--given high detection limits selected--1989 and 1976 contamination levels could not be compared.

Median concentration of chromium was 35 μg/g in 1989 compared to 64.1 μg/g in 1976, testifying to a general decrease in chromium contamination of sediment in the subsystem. Values ranged from 11 to 83 μg/g (1976 maximum was 1 050 μg/g, in the St. Charles River). Improvements were especially marked downstream of Massena (59 μg/g compared to 122 μg/g in 1976) and in the northern part of the St. Zotique basin (48 μg/g compared to 464 μg/g in 1976) (Figure 16). As with copper and zinc, chromium concentrations on the north side differed significantly from those on the south side. In 1989, chromium concentrations were highest downstream of Cornwall, in the St. Zotique and Lancaster basins and in the shallows of the upstream third of the lake; these areas were only moderately contaminated however.

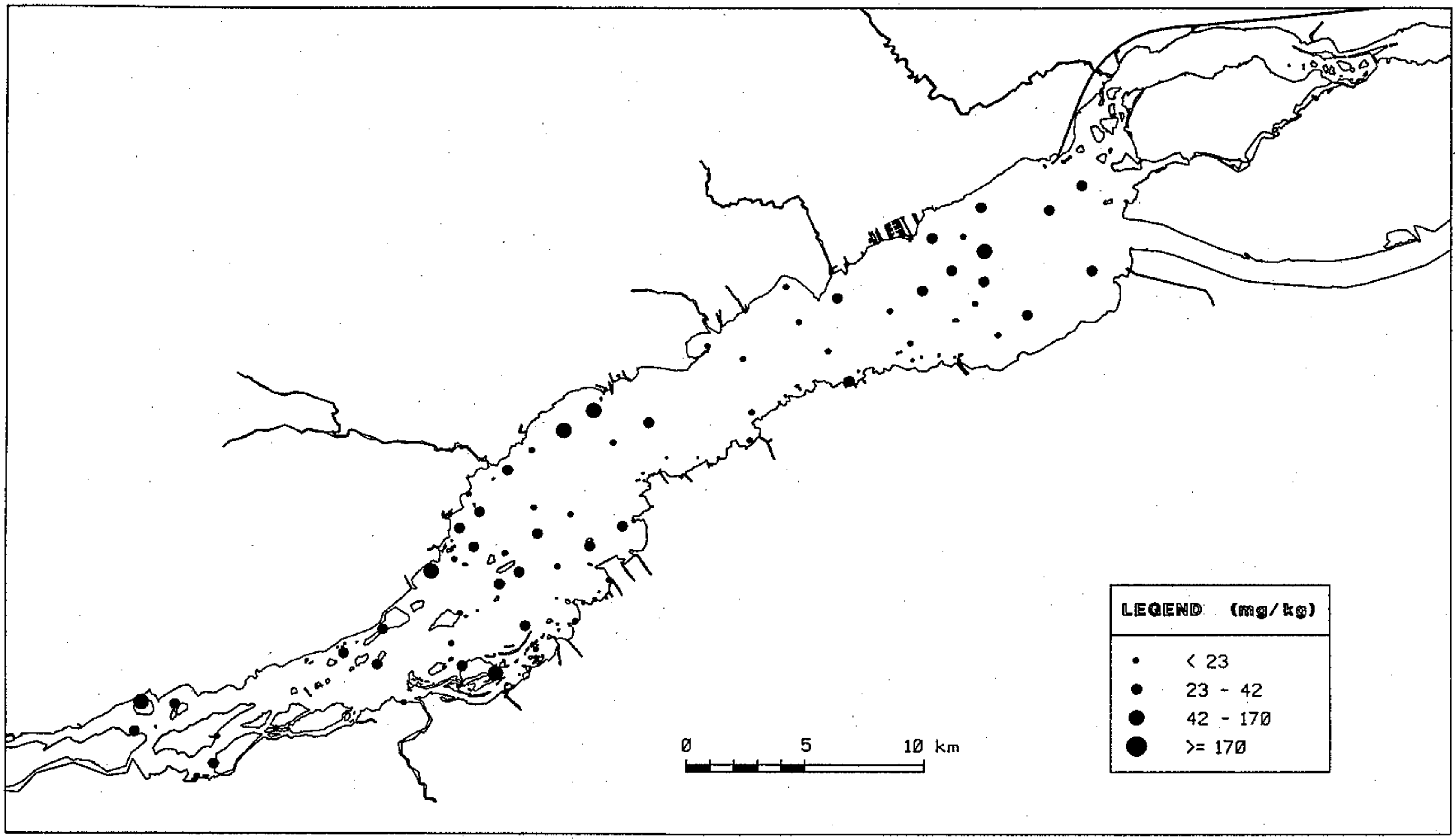


Figure 14 ***Lead distribution in Lake St. Francis sediment (1989)***

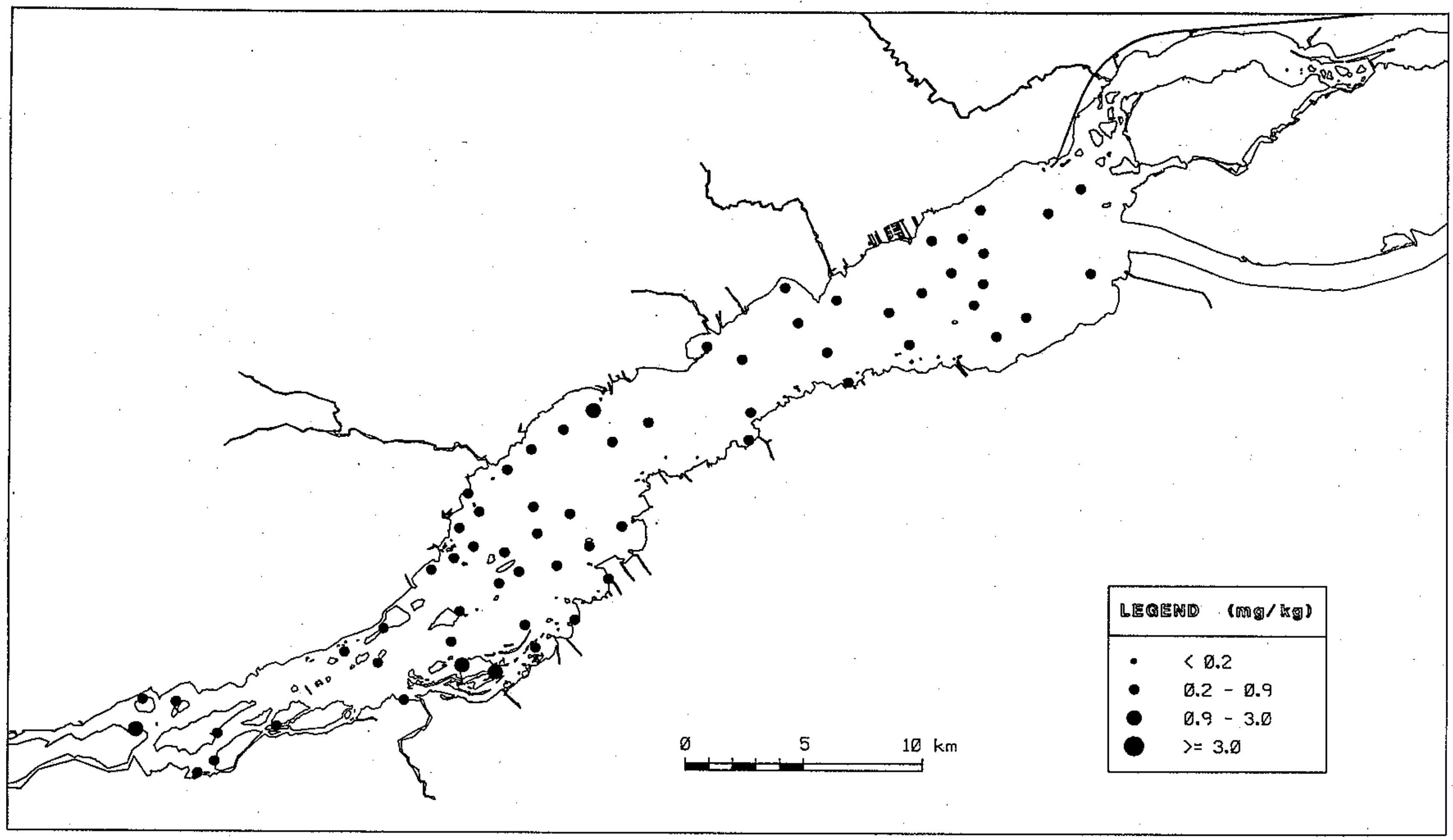


Figure 15 Cadmium distribution in Lake St. Francis sediment (1989)

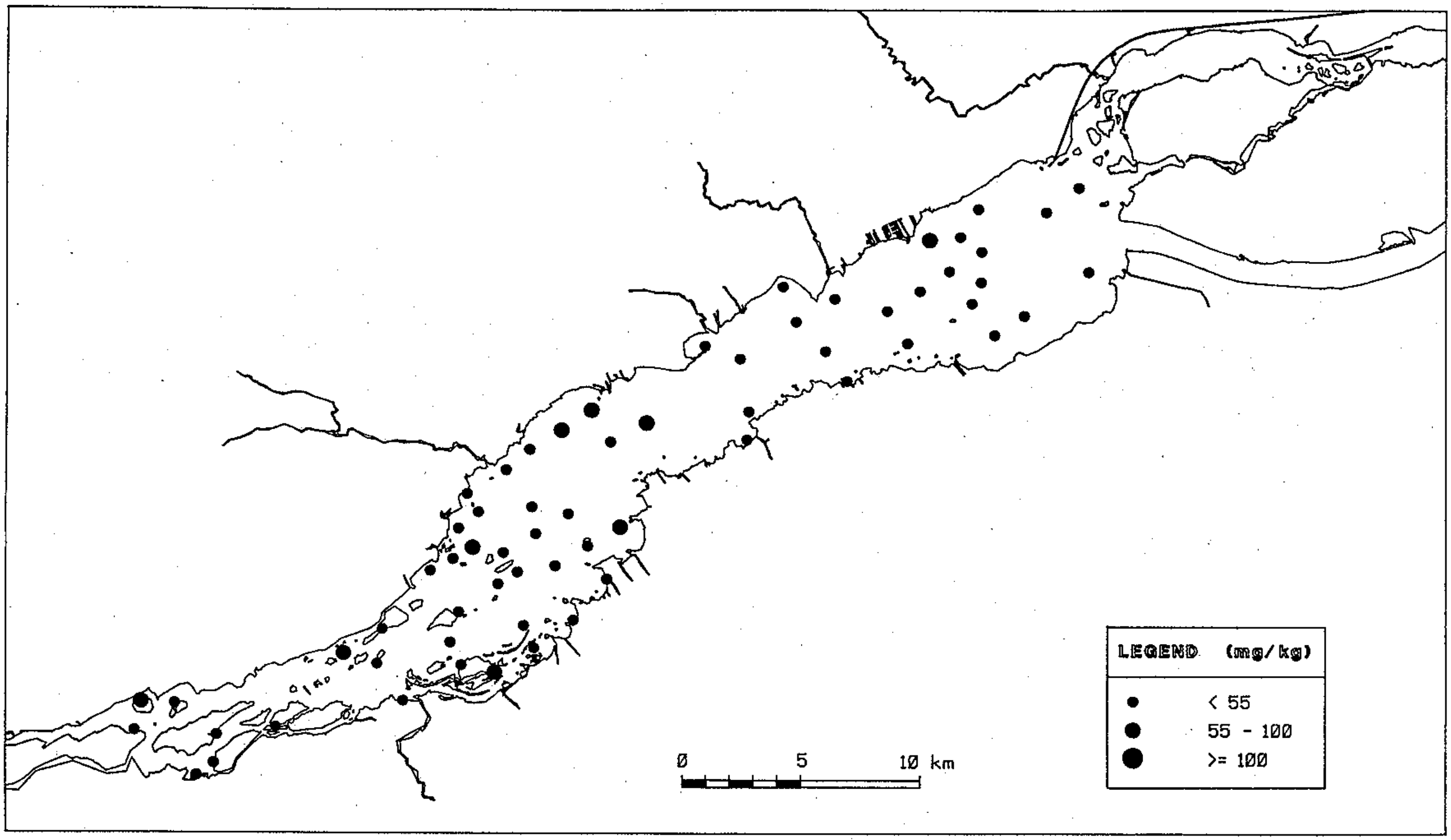


Figure 16 ***Chromium distribution in Lake St. Francis sediment (1989)***

Nickel contamination also decreased over the decade. Sediment concentrations are now background levels (Figure 17). Median was 20.6 μg/g in 1989 compared to 33.8 μg/g in 1976, and maximum was 45.5 μg/g in 1989 compared to 81.2 μg/g in 1976. Maximum value in 1989 was obtained on the south shore, in the shallows of the upstream third of the lake. On the whole, however, concentrations varied little from one part of the lake to the next; most were close to average value.

Conclusion. Contamination of sediment in subsystem 1--of which Lake St. Francis is the main component--fell dramatically after input to the subsystem decreased significantly with the limitation of discharges to the Cornwall area and other measures to reduce input in the Massena area. Whereas major contamination was noted in 1976--mainly downstream of Cornwall, in the northern part of the St. Zotique basin, near Île aux Chats and in the St. Charles River--by 1989 the situation had on the whole greatly improved.

In fact, apart from the area encompassing the vicinity of Île aux Chats and the St. Charles River (trends in this area, contaminated mainly by local sources, could not be determined), in 1989 there were no longer spots where heavy metal concentrations exceeded TET quality criteria. The most dramatic improvements were noted downstream of Cornwall, downstream of Massena and in the northern part of the St. Zotique basin. These areas, together with the shallows and the Lancaster basin are still the most contaminated parts of subsystem 1. The central part of the lake has always been less contaminated than the north and south sides. In 1989, sediment quality data was obtained for parts of Lake St. Francis that had not been measured in the past.

The only parts of the subsystem where sediment quality remains to be determined are the Beauharnois Canal, the international section of the St. Lawrence and the St. Charles River.

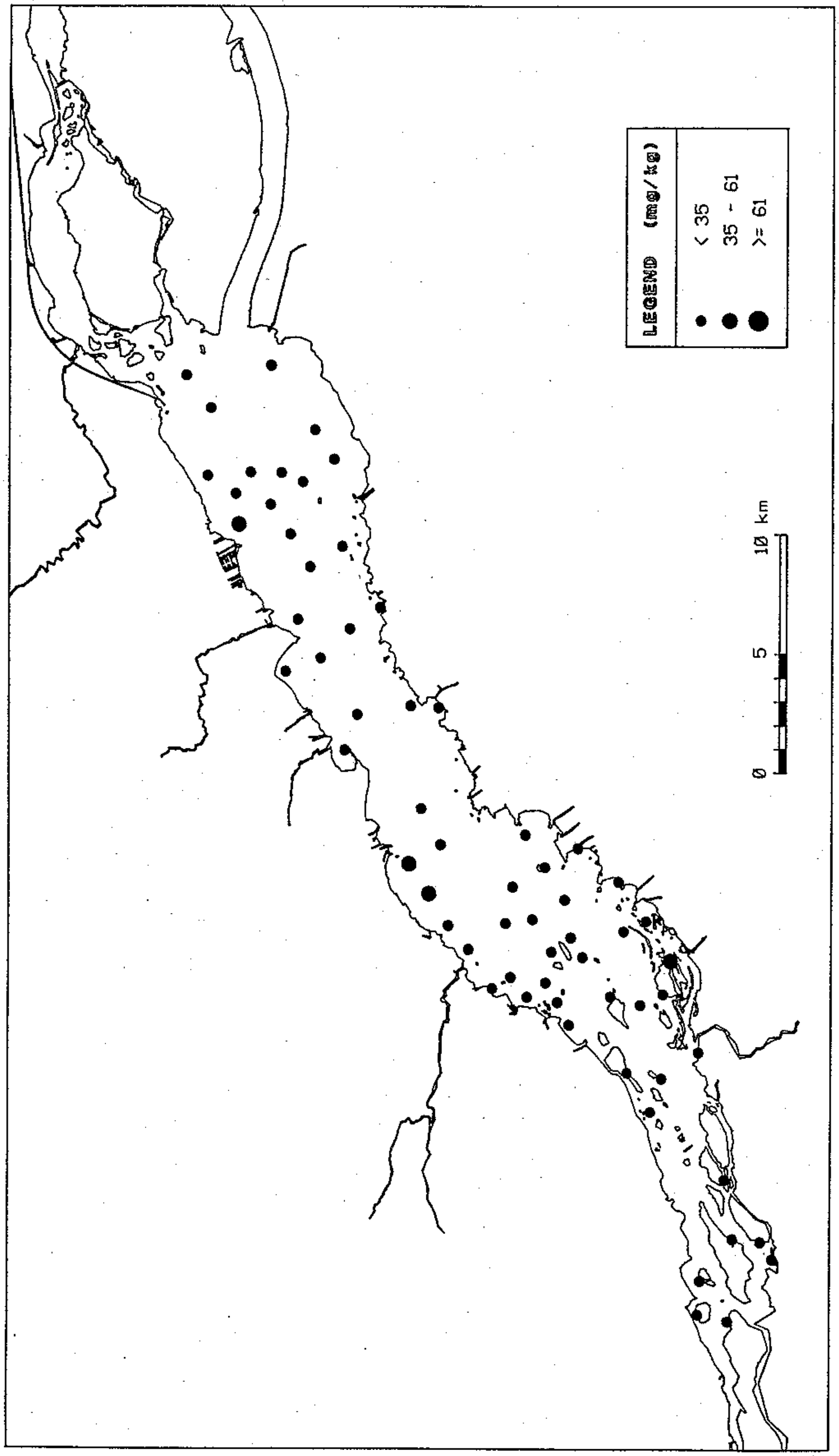


Figure 17 Nickel distribution in Lake St. Francis sediment (1989)

4.2 Subsystem 2a: Lake St. Louis

4.2.1 Physiography and dynamics. Water dynamics are more complex here than in Lake St. Francis because Lake St. Louis has two major affluents: it receives waters of the Ottawa via the Vaudreuil and Ste. Anne channels circling Île Perrot and waters of Lake St. Francis via the Pointe des Cascades Dam and the Beauharnois Canal. There are also other smaller but nonetheless qualitatively significant tributaries: the Châteauguay and St. Louis rivers on the south side of the lake and Bouchard Creek on Montréal Island.

Lake St. Louis is triangular. At the base of the triangle are the main affluents and at the top are the Lachine rapids, the lake outlet. The lake covers 148 km^2 (Préfontaine, 1942). Maximum length is 23 km and maximum width 10 km. The lake is at elevation 21.3 m (Hydrotech, 1989) and is controlled by a narrowing of the flow section at the large jetty in Lachine.

Average depth of Lake St. Louis is 3 m (Pageau, 1971). There is a deep depression (27.75 m) in the lake at the Beauharnois Canal outlet as well as a couple of shallower basins (12 to 15 m) near Dowker and Dorval islands (Figure 18). The St. Lawrence Seaway runs through the southern part of Lake St. Louis, between the Beauharnois Canal outlet and the seaway entrance. This man-made channel is a minimum 8.4 m deep. The lake is shallower close to both shores, on the south side of Îles de la Paix, in Valois Bay, in Grande Anse de l'Île Perrot and in the centre of the lake around St. Jean Creek where there are a series of shallows on both sides of the seaway.

Mean annual discharge of the St. Lawrence at the Lake St. Louis outlet was 9 047 m^3/s between 1980 and 1989 (Table 13). Maximum mean annual discharge during the period was 10 100 m^3/s (in 1986) and minimum was 7 990 m^3/s (in 1989). Average residence time is 12 hours in the main channel (Hydrotech, 1989). Variations in flow are greater in Lake St. Louis than in Lake St. Francis and are to a large extent caused by the Ottawa River.

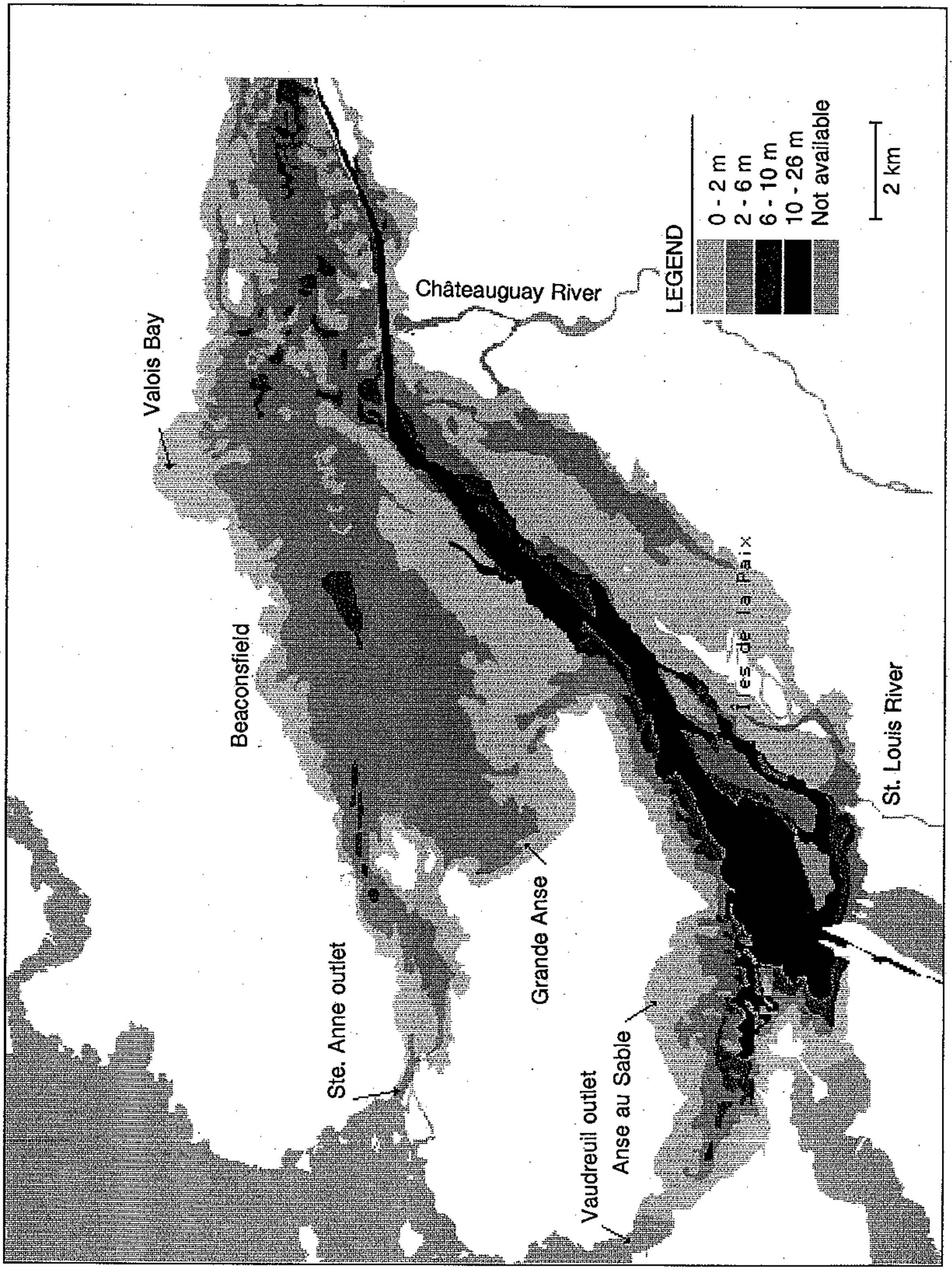


Figure 18 **Bathymetry of Lake St. Louis**

Table 13 ***Mean annual discharge of the St. Lawrence River at LaSalle between 1980 and 1989 (Environment Canada, 1990)***

Year	Mean annual discharge (m^3/s)
1980	9 190
1981	9 210
1982	8 740
1983	9 160
1984	9 390
1985	9 450
1986	10 100
1987	9 100
1988	8 140
1989	7 990
Mean (1980-89)	9 047

Mean annual tributary discharges are as follows: Ste. Anne channel, 433 m^3/s; Vaudreuil channel, 393 m^3/s; Châteauguay River, 34 m^3/s; and St. Louis River, 2.1 m^3/s (Asseau, 1992b).

The waters of the St. Lawrence River are green and highly mineralized. They come from the drainage basin of the Great Lakes and the international section of the St. Lawrence, highly industrialized areas. These water contribute an average 90 percent of the flow of Lake St. Louis and run mainly along the south side of the lake. The waters of the Ottawa River are brown and only slightly mineralized; they run along the north side of the lake, along Montréal Island. The encounter between these two water masses causes a third mass to form with characteristics between those of the two original masses. Size and position of this third mass of water depends on flow of the two affluents.

It is the presence of these two major affluents from different drainage basins, together with the complex bathymetry of the lake (which is partly artificial), that makes velocities and water mass distribution in the lake so highly complex. Hydrotech (1989) gives the following description (our translation):

> The divide between the waters of the St. Lawrence and Ottawa rivers on the left side of the lake was identified for a number of flows to within the vicinity of Dorval Island. Main findings were as follows:
>
> Waters from Ste. Anne de Bellevue run along the left shore, gradually mixing with waters of the St. Lawrence (Great Lakes).
>
> Waters from Vaudreuil are trapped in an immense eddy downstream of Île des Cascades before they continue on around Île Perrot, mixing with the waters of the St. Lawrence and the partially mixed waters from Ste. Anne de Bellevue. Conditions are not the same during low water as during floods.
>
> The waters of the St. Louis and Châteauguay rivers, on the other hand, which are generally very heavily loaded with sediment, run along the right shore and then down the St. Lawrence Seaway. Bottom contamination along the south shore of Lake St. Louis seems at first glance then closely connected with input from the St. Louis and Châteauguay rivers.
>
> The different masses of water are not stable; on the contrary, they change with time, location and flow. Spatiotemporal distribution in Lake St. Louis is transverse and nonuniform.
>
> Since Rivière Des Prairies and Rivière des Mille Îles drain only the waters of the Ottawa River--except during exceptional floods when the St. Lawrence overflows into Lake of Two Mountains--the greater Montréal area (Montréal Island as well as Île Jésus, Île Bizard and Île Perrot) is bathed exclusively by waters of the Ottawa River.

Fastest velocities (> 60 cm/s) are at the lake outlet, in the seaway and along the south shore of Île Perrot between Pointe Fortier and Pointe du Moulin; these velocities prevent sedimentation of fine material. Current is slow in the shallows in the centre of the lake colonized by submerged weedbeds, along the south shore immediately upstream and downstream of the Beauharnois Dam, downstream of Îles de la Paix and at the south-shore canal entrance. On the left side of the lake, current is slowest in Grande Anse de l'Île Perrot and along Beaconsfield. Currents speed up starting at Dorval, where the flow section narrows, and this affects particle-size distribution locally (Sydor, 1978). In addition, currents are not linear but are affected by bathymetry and by size of the water masses from the Ottawa and St. Lawrence rivers. A large eddy is generated at the Beauharnois Canal outlet because of local bathymetry and the islands downstream. As a result, some contaminants transported by the St. Louis River are dispersed along the shoreline upstream.

Mass balance was estimated by Hydrotech (1989) at 2 600 000 t/a, or a suspended solids load of 8 to 10 mg/L at the Lake St. Louis outlet. According to Hydrotech, the Ottawa River contributes one-tenth the volume of solids (210 000 t/a) contributed by Lake St. Francis (2 300 000 000 t/a, or 7 to 8 mg/L at the Lake St. Louis inlet). Though its discharge is relatively small, the Châteauguay River nonetheless contributes a total solids load of 70 000 t/a. There is substantial sedimentological activity in the Châteauguay River--especially during spring and fall floods, when maximum concentrations can easily exceed 500 mg/L (Hydrotech, 1982). Contribution of the St. Louis River is estimated at 13 000 t/a--also quite high given the very small discharge of this river (2.1 m^3/s). Input from other sources is estimated at 17 000 t/a. Sedimentation occurs mainly in the spring; the sediment is transported subsequently and net accumulation is generally zero.

More recently, Carignan at al. (1993) estimated sediment accumulation rates at 4.4 $kg/m^2/a$ in the deep depression at the Lake St. Louis entrance, 2.6 $kg/m^2/a$ in the middle of the lake, and 3.1 $kg/m^2/a$ for the lake as a whole.

4.2.2 Sources of contamination

Industrial discharges. The following information on toxic input comes from Asseau (1992b). There are four targeted plants in subsystem 2a. Alcan (Alcan Chemicals and Smelters Ltd.) operates a metallurgical plant in Melocheville that performs primary aluminium treatment. The plant has two outfalls, one for rainwater and cooling water and the other for sanitary sewage. Only the outfall for rainwater and cooling water was sampled; this outfall empties into the St. Charles River (mean discharge = 0.0394 m^3/s). The other outfall is connected to the municipal sewage system.

PPG Canada Inc. operates an organic chemicals plant in Beauharnois that manufactures sodium hypochlorite. The plant has six outfalls: process waters are emptied into the St. Louis River, but rainwater is discharged to the St. Lawrence. Sanitary sewers are connected to the municipal sewage system. One of the outfalls discharging rainwater and one of the sanitary sewage outfalls were contaminated by mercury in 1988 and had to be condemned in 1990. Total discharge of the process-water outfall and the outfalls contaminated by mercury was 0.177 m^3/s.

Elkem Metal Canada Inc. operates a metallurgy plant in Beauharnois that manufactures iron-manganese and silicon-manganese alloy chips. The plant was shut down in 1989. Plant process waters used to discharge directly to the river. By 1989, only cooling water was being discharged to the river (0.254 m^3/s); this is the only effluent that has been characterized.

Domtar Inc. operates a pulp and paper mill in the municipality of Beauharnois that converts chemical pulp to fine paper. The plant has two outfalls: one discharges process water (0.0869 m^3/s) to the St. Louis River, and the other conveys cooking liquor to a treatment unit. Before 1989, the latter outfall discharged cooking liquor directly to the river without treatment. A total of 41 m^3 were discharged with each cooking; there are no data on cooking frequency.

Table 14 summarizes known input from the four plants described above (Asseau, 1992b). In 1989, Elkem Metal Canada Inc. contributed most to industrial contaminant loads--loads of lead, cadmium, mercury and copper in particular. PPG contributed significantly to mercury load. Alcan also contributed to mercury load, but to a lesser extent.

Table 14 ***Measured industrial metal (Hg, Cu, Zn, Pb, Cd, Cr and Ni) input to Lake St. Louis (Asseau, 1992b)***

Metal	Alcan	Domtar	Elkem	PPG
Mercury (kg/d)	0.0068	<0.0024	0.0088	0.044
Copper (kg/d)	<0.10	<1.2	2.2	--
Zinc (kg/d)	<0.053	<1.2	8.8	--
Lead (kg/d)	0.27	--	8.8	--
Cadmium (kg/d)	<0.034	--	2.2	<0.24
Chromium (kg/d)	<0.034	--	<2.2	+3 <1.2 +6 <0.37
Nickel (kg/d)	<0.17	--	--	--

Base year: 1989
Inaccuracy of industrial input: about 30%
-- No data available

Tributaries. Table 15 lists estimates of toxic input from all tributaries in the region.

Table 15 ***Daily mean tributary metal (Cu, Zn, Pb and Ni) input to Lake St. Louis (Asseau, 1992b)***

Metal	Vaudreuil	Ste. Anne	Châteauguay	St. Louis
Copper (kg/d)	73	58	13	0.6
Zinc (kg/d)	853	109	30	1.2
Lead (kg/d)	29	36	196	0.2
Nickel (kg/d)	41	35	15	0.5

Base years: 1985-1988
Inaccuracy of tributary input: about 25%

Volume input of these tributaries is significant and can contribute to contaminating Lake St. Louis and the lesser La Prairie basin. The Vaudreuil and Ste. Anne channels have comparable flows, but there is much more toxic input from the Vaudreuil than the Ste. Anne channel (67 percent compared to 16 percent of total toxic input). Toxic load of the Châteauguay River is comparable to that of the Ste. Anne channel (17 percent of total input), but type of contamination is different. Input of the reference metals from the St. Louis River seems to be negligible (0.2 percent of total input), though characterization surveys indicate the St. Louis River is a major local source of PCBs and mercury (Carignan and Alves, 1978; Sérodes and Talbot, 1978).

Copper loads of the Vaudreuil and Ste. Anne channels are relatively similar though data accuracy level is low; these channels contribute 90 percent of total tributary copper load. The Châteauguay River contributes 9 percent of total tributary copper load. Copper input from the St. Louis River is negligible.

Zinc comes mainly from the Vaudreuil channel (86 percent of total zinc input). In fact, the Vaudreuil channel ranks third among the tributaries of the St. Lawrence River for zinc input. About 11 percent of total zinc input comes from the Ste. Anne channel, 3 percent comes from the Châteauguay River and less than 1 percent comes from the St. Louis River.

The Châteauguay River is a major source of lead, contributing 75 percent of total lead input. The remaining 25 percent comes from the Vaudreuil and Ste. Anne channels, which contribute about equally to lead load in Lake St. Louis.

Spring loads discharged to the Montréal area are much greater than summer loads: copper load is 2.6 times as great, zinc load is 30 times as great and lead load is 4.5 times as great (Asseau, 1992b).

Municipalities. In 1989, Lake St. Louis received wastewater from nine riverside municipalities, four of them equipped with wastewater treatment facilities. These municipalities have close to 70 000 inhabitants; wastewater generated by 20 percent of this population was treated. Known municipal loads discharged to Lake St. Louis are as follows: Cu, 1.6 kg/d; Zn, 5.84 kg/d; and Pb, 2.87 kg/d (Table 16). Total municipal load is comparable to municipal loads discharged to Lake St. Francis and Lake St. Pierre, but is small compared to those discharged to the La Prairie basin and around Québec City.

Table 16 Municipal metal input (Cu, Zn and Pb) to Lake St. Louis in 1989 (Asseau, 1992b)

Municipality	Cu (kg/d)	Zn (kg/d)	Pb (kg/d)
Notre Dame de l'Île Perrot	0.017	0.043	0.021
Pincourt and Terrasse Vaudreuil	0.15	0.38	0.19
Île Perrot	0.13	0.32	0.16
Beauharnois and Maple Grove	0.064	0.16	0.080
Châteauguay	1.2	4.9	2.4
Kahnawake	--	--	--
Melocheville	0.015	0.038	0.019
TOTAL	1.6	5.84	2.87

Base year: 1989
Inaccuracy of municipal input: about 50%
-- No data available

The municipality of Châteauguay (38 500 inhabitants) is the largest contributor of the three reference metals (82 percent of the total load). About 13 percent of the total municipal load comes from Pincourt, Terrasse Vaudreuil and Île Perrot. The other municipalities contribute the remaining 5 percent of the total municipal load.

Zinc heads the list of wastewater contaminants from these municipalities, comprising about 57 percent of total contaminant load. Next comes lead (28 percent) and then copper (16 percent). The three metals almost always appear in this order in municipal discharges to the St. Lawrence River.

Summary. Upstream reaches of the St. Lawrence River contribute 90 percent of total discharges to this subsystem. The other 10 percent comes from tributaries, municipalities and industrial plants. Table 17 shows toxic input from upstream reaches of the St. Lawrence River as well as loads from the other three main sources of contamination of Lake St. Louis.

Table 17 Annual metal input (Cu, Zn and Pb) from the four main sources of contamination of Lake St. Louis (Asseau, 1992b)

Source	Cu (kg/a)	Zn (kg/a)	Pb (kg/a)	%
Industrial plants	801	3 204	3 303	0.4
Tributaries	52 779	362 518	95 338	29.0
Municipalities	584	2 117	1 058	0.2
Upstream St. Lawrence River reaches	262 894	919 997	58 392	70.4
TOTAL INPUT	317 058	1 287 836	158 091	100

Inaccuracy of industrial input: 30%
Inaccuracy of tributary input: 25%
Inaccuracy of municipal input: 50%
Inaccuracy of input from upstream St. Lawrence River reaches: 25%

Lake St. Louis receives total annual input of more than 300 000 kg of copper, 1 200 000 kg of zinc and 150 000 kg of lead. Upstream reaches of the St. Lawrence are the main source of contamination, providing 70 percent of total input. Next come the tributaries with 29 percent of total input, followed by industrial and municipal discharges, whose contribution to contamination by the three reference metals is negligible. Industrial load may however have been underestimated because the reference metals were not measured in all effluents.

To be precise, upstream reaches of the St. Lawrence contribute 83 percent of total copper load, 71 percent of total zinc load and 37 percent of total lead load.

Tributaries contribute 17 percent of total copper load, 28 percent of total zinc load and 60 percent of total lead load. Lead differs from the other reference metals in that it comes mainly from tributaries not from upstream St. Lawrence River reaches. Industrial plants and municipalities contribute less than 1 percent of total subsystem load of each of the reference metals.

4.2.3 Particle-size distribution. Figure 19 shows dominant size fractions in Lake St. Louis. Particle size varies between Anse au Sable and the Beauharnois Canal; sands and gravels mix with silts and clays (Table 18). Along the south shore, opposite Melocheville, silt dominates. In this section of the lake, Ottawa River waters mix with those of upstream St. Lawrence River reaches; mixing, currents and substrata are complex here since they are influenced by flows from both these streams.

Most of the discharge from upstream St. Lawrence River reaches enters Lake St. Louis at the Beauharnois Canal outlet. Distinctive features of this section of the lake are its depth, the fast velocities along the path of the waters from the Beauharnois Canal and the seaway, and a large eddy generated between the seaway and the south shore upstream of Îles de la Paix.

The Beauharnois basin has a predominantly gravel bottom. The basin is not favourable for sedimentation despite its depth because of the substantial discharge from the Beauharnois Canal. The left shore of this stretch, between Pointe Fortier and Pointe du Moulin, north of the seaway, is also a transport and erosion zone where coarse substrata dominate.

Downstream of the Beauharnois basin right to the lake outlet, the seaway floor is dominated by coarse substrata. The seaway is the lake's main axis of streaming and velocities are fast in the seaway channel, preventing sedimentation of fine material. At the head of the rapids, between Lachine and Tekakwitha Island, the bottom is rocky.

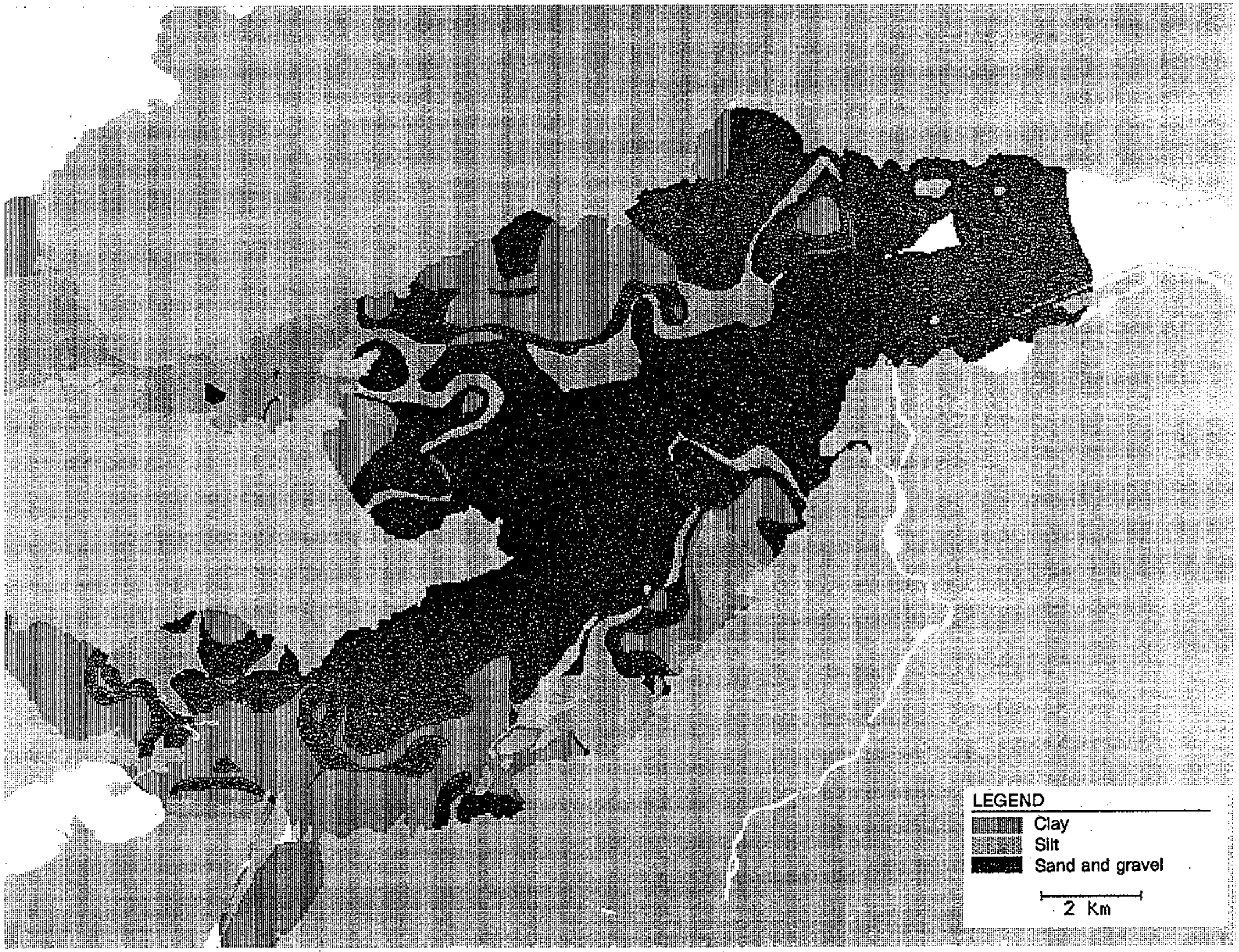


Figure 19 **Dominant size fractions in Lake St. Louis**

Table 18 Dominant size fractions in Lake St. Louis

Area	Size class	Number of stations	Average %	Standard deviation	Minimum %	Maximum %
Lake St. Louis	Clay Silt Sand	291 291 291	26 29 48	20 20 32	4 15 1	67 92 88
St. Louis River	Clay Silt Sand	17 17 17	38 34 27	21 20 29	3 4 1	77 62 90
Îles de la Paix	Clay Silt Sand	22 22 22	24 43 39	16 17 29	0 0 4	52 65 100
Centre	Clay Silt Sand	33 33 33	21 30 60	18 21 35	0 0 1	76 71 100
Beaconsfield	Clay Silt Sand	42 42 42	29 30 36	20 21 30	2 4 1	74 70 92
Valois Bay	Clay Silt Sand	29 29 29	20 22 55	13 14 18	1 0 9	57 50 90
Anse au Sable	Clay Silt Sand	26 26 26	43 24 34	24 12 34	3 1 1	76 42 96

Clay dominates on the south shore opposite Pointe Thibodeau; this deposit is affected by waters from upstream reaches of the St. Lawrence received via the Beauharnois Canal and by the highly deteriorated waters of the St. Louis River. Silt and clay are the dominant fractions almost everywhere along the south shore between Beauharnois and St. Jean Creek. This shallow area bounded on the north by Îles de la Paix is a major contaminant sink (Sérodes, 1978; Carignan and Alves, 1978; Sérodes and Talbot, 1978; Jarry et al., 1985; Champoux and Sloterdijk, 1988). It is affected by the St. Louis River and effluents from industrial plants in the Beauharnois area. The coarse sediment of Maple Grove Cove is only partially typical of substrata in this stretch--which is generally dominated by fine material, mainly silt interspersed with pebbles.

The rocky bottom at the Ste. Anne outlet (on the left side of the lake, bathed by the waters of the Ottawa River) is gradually supplanted by finer material dominated by silt upstream of Dowker Island. Downstream on this side of the lake, substrata are diversified because of the complexity of the bottom and the currents. Sands are nonetheless the dominant fraction in most of the north side of Lake St. Louis. There are areas of sedimentation near Beaconsfield, in Valois Bay, and in Grande Anse d'Île Perrot, close to Pointe du Domaine. Another area of sedimentation not shown in Figure 19 is around the Lachine jetties.

The weedbeds in the centre of Lake St. Louis grow on substratum dominated by silt. This area in the centre of the lake is probably a temporary fine-material sink controlled by seasonal growth of submerged weedbeds. Between the weedbeds and the sandy strip farther north is a linear strip of sandy silt running in the direction of the current between Grande Anse and Valois Bay. This strip is in the water mixing zone.

The current is very fast at the Lachine rapids (the Lake St. Louis outlet) and the bottom is rocky.

4.2.4 Physical chemistry. Lake St. Louis sediment has been known to be contaminated since publication of the work of Centreau in the mid-1970s. In 1976, major mercury contamination was detected, mainly in the southeastern part of Lake St. Louis but also in Valois Bay. Median mercury concentration in the lake as whole was 0.73 µg/g (Table 19), with maximum values at the mouth of the St. Louis River (median was 3.48 µg/g and maximum 86.91 µg/g) (Tables 20 and 21).

Table 19 Lake St. Louis sediment quality statistics

Year	Metal	Number of samples	% samples below detection level	Mean (µg/g)	Standard deviation (µg/g)	Median (µg/g)	Minimum (µg/g)	Maximum (µg/g)
1976*	Pb	50	0	26.62	31.97	23.00	0.00	200.00
	Cd	51	0	7.68	3.00	8.00	2.00	19.00
	Zn	51	0	176.63	104.68	176.00	33.20	663.00
	Hg	48	0	8.56	19.17	0.73	0.02	86.92
	Ni	51	0	38.54	16.29	41.10	7.00	88.00
	Cu	51	0	35.77	16.52	37.20	7.83	73.70
	Cr	51	0	68.73	26.81	68.40	14.90	150.00
1984 1985**	Pb	47	0	43.64	24.29	36.00	10.00	138.00
	Cd	21	14	2.13	3.13	1.00	0.20	14.00
	Zn	47	0	242.93	141.26	179.00	54.00	686.00
	Hg	48	0	1.51	5.03	0.42	0.02	34.90
	Ni	47	0	37.00	12.05	35.00	18.00	77.00
	Cu	48	0	39.58	22.69	35.00	9.00	131.00
	Cr	34	0	79.19	23.15	72.00	39.00	140.00

* Sérodes (1978) ** Champoux et al. (1988)

Table 20 ***Median metal concentrations in six areas of Lake St. Louis (µg/g)***

Year	Metal	St. Louis River	Îles de la Paix	Centre	Beaconsfield	Valois Bay	Anse au Sable
		Median	Median	Median	Median	Median	Median
1976	Pb	9.00	26.00	17.00	30.00	30.00	30.00
	Cd	9.00	8.00	7.00	7.00	8.00	8.00
	Zn	203.00	150.00	204.00	185.00	217.00	161.00
	Hg	3.48	0.81	0.42	0.22	1.05	0.04
	Ni	54.00	41.10	24.60	33.90	45.10	52.10
	Cu	54.80	37.70	20.90	27.10	37.80	34.70
	Cr	80.20	67.60	53.00	61.20	93.50	75.60
1984 1985	Pb	40.00	32.00	32.00	59.00	44.00	60.00
	Cd	1.20	1.00	1.00	1.00	0.20	0.00
	Zn	155.00	160.00	179.00	390.00	314.00	349.00
	Hg	1.38	0.54	0.33	0.47	0.27	0.34
	Ni	45.00	34.00	23.00	48.00	32.00	52.00
	Cu	39.00	34.00	20.00	52.00	23.00	47.00
	Cr	78.00	66.00	55.00	107.00	70.00	117.00

Table 21 Maximum metal concentrations in six areas of Lake St. Louis (µg/g)

Year	Metal	St. Louis River	Îles de la Paix	Centre	Beaconsfield	Valois Bay	Anse au Sable
		MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM
1976	Pb	62.00	105.00	66.00	37.00	200.00	63.00
	Cd	13.00	10.00	15.00	10.00	19.00	11.00
	Zn	293.00	230.00	663.00	215.00	295.00	444.00
	Hg	86.92	5.84	1.49	0.34	1.61	0.62
	Ni	81.20	88.00	55.50	47.00	49.50	62.80
	Cu	73.70	53.10	69.50	40.10	48.30	65.70
	Cr	117.00	138.00	92.90	102.00	150.00	90.40
1984 1985	Pb	101.00	49.00	64.00	62.00	71.00	65.00
	Cd	14.00	1.40	2.70	2.80	1.60	1.70
	Zn	686.00	229.00	534.80	440.00	481.00	465.00
	Hg	34.90	4.78	0.42	0.59	0.28	0.52
	Ni	77.00	45.00	48.00	51.00	38.00	55.00
	Cu	105.00	57.00	56.00	57.00	32.00	68.00
	Cr	140.00	87.00	100.00	107.00	70.00	118.00

Mercury levels were also very high southeast of Îles de la Paix and in Valois Bay (maxima of 5.84 and 1.61 µg/g, respectively; figures 20 and 21). A relation was established between contamination of the southeast part of Lake St. Louis and discharges to the lake from metallurgy and organic chemicals plants (Sérodes and Talbot, 1978).

Sediment contamination in the part of Lake St. Louis upstream of the St. Louis River may be related to the large eddy generated in the water mass in this area that pulls some of the water mass from the St. Louis River upstream with its contaminants. The eddy also explains the rapid drop in contamination downstream of the mouth of the tributary; despite favourable conditions for sedimentation south of Îles de la Paix, much of the water that bathes this area comes from the St. Lawrence River.

Moderate mercury contamination (median of 0.42 µg/g) was noted in the central part of the lake--formed by Grande Anse de l'Île Perrot and the shallows colonized by weedbeds--as well as at certain stations (north side of Îles de la Paix, 0.85 µg/g; upstream of Tekakwitha Island, 0.65 µg/g; and Anse au Sable, 0.62 µg/g). Mercury concentrations in sediment at these stations were worrisome. Areas where mercury contamination was not as great were the Vaudreuil outlet and zones like the seaway channel which are unfavourable for sedimentation.

A close link was established between mercury contamination of the mouth of the St. Louis River and industrial discharges to the St. Louis River (Sérodes et al., 1978). Contamination at Îles de la Paix was also attributed to industrial discharges. The pattern of contamination of Valois Bay suggests a local source, that is, discharges from outfalls on the left shore of the lake. Contamination of Anse au Sable seems attributable to the Ottawa River via the Vaudreuil channel. The complex and variable hydrodynamic conditions in the centre of the lake make it impossible to determine the exact relation between mercury distribution pattern and contaminant sources.

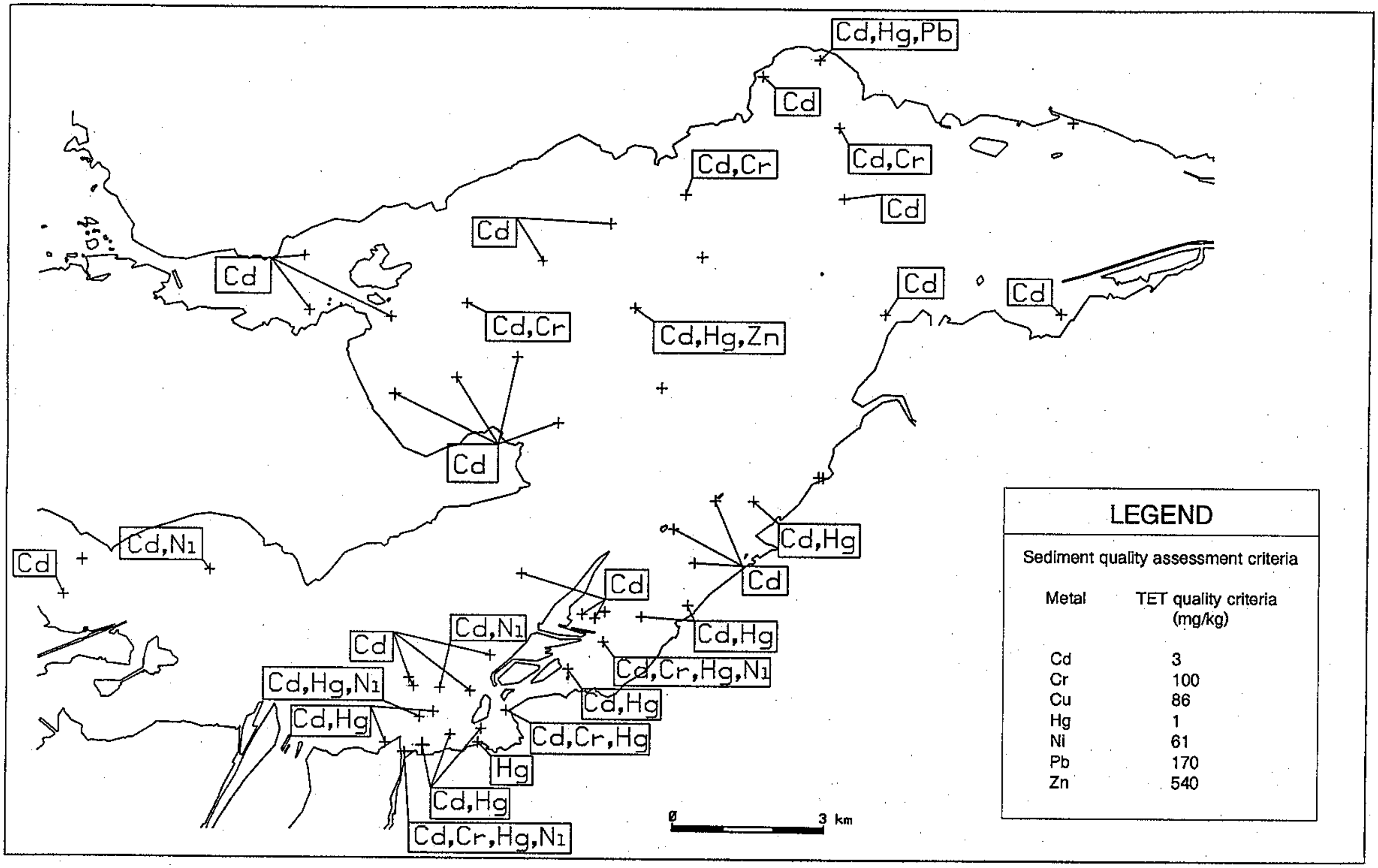


Figure 20 ***Exceedences of TET quality criteria in Lake St. Louis (1976)***

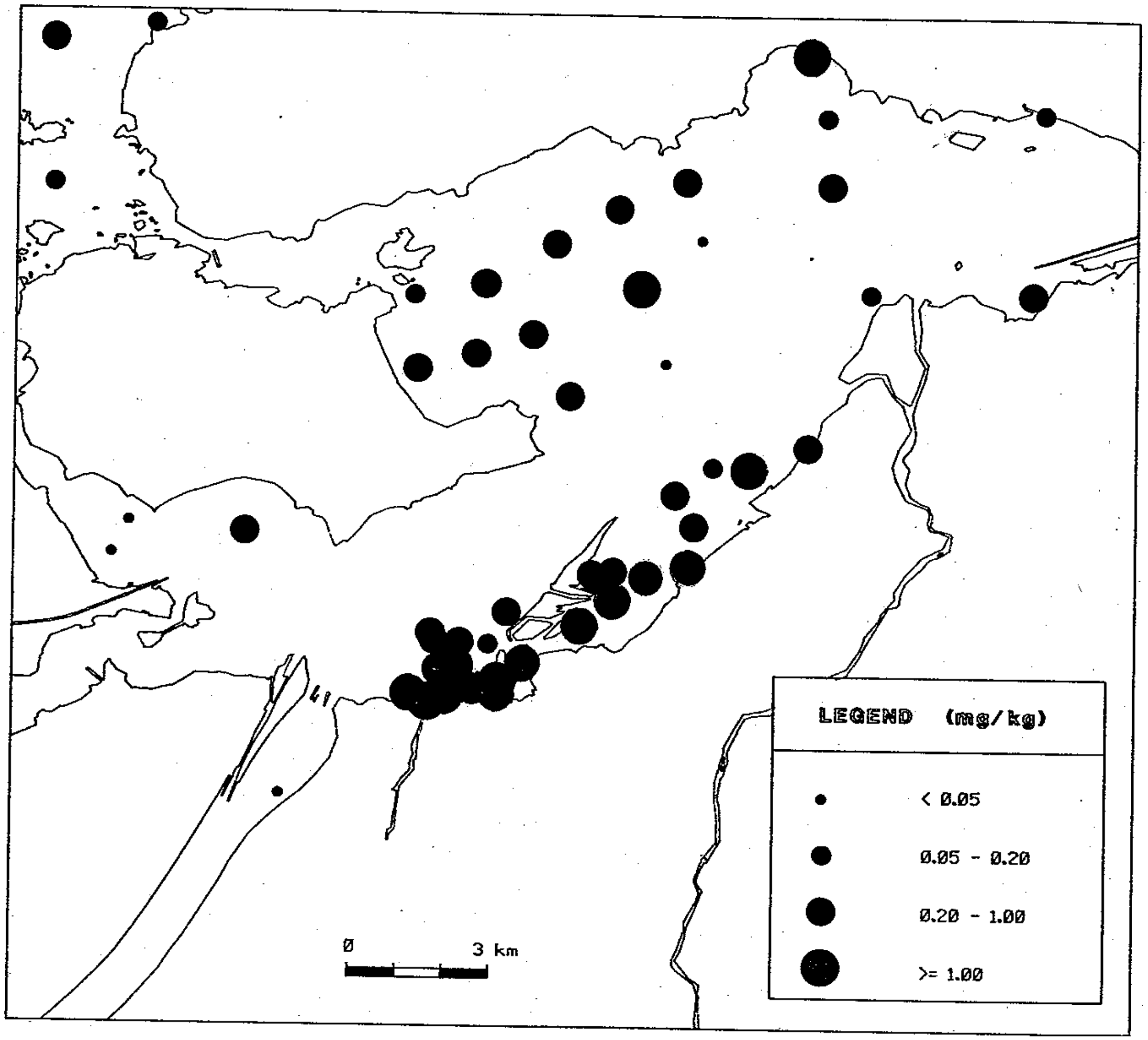


Figure 21 *Mercury distribution in Lake St. Louis sediment (1976)*

Lake St. Louis sediment was far less contaminated by copper than by mercury. Median was 37.2 μg/g. Highest copper concentration (73.7 μg/g) was detected at the mouth of the St. Louis River. Many measured concentrations were background levels; when enrichment was noted it was moderate (Figure 22). Copper enrichment, unlike that of mercury, was diffuse and hence its origin is difficult to determine.

Median concentration of zinc was 176 μg/g, with maximum concentration (663 μg/g) in the centre of the lake. Highest median concentrations were in Valois Bay, at the mouth of the St. Louis River and in the centre of the lake (Figure 23); enrichment was moderate in these spots. Concentrations of concern were also noted at some Anse au Sable stations and on the north side of Dowker Island. Zinc levels were low in areas unfavourable for sedimentation.

The data show slight lead enrichment. Median for the lake as a whole (23 μg/g) was background level (23 μg/g). Maximum concentration (200 μg/g) was detected in Valois Bay, the most lead-contaminated area of Lake St. Louis. Moderate contamination was detected at a few stations, but in general Lake St. Louis sediment was only slightly lead-enriched in 1976 (Figure 24). Lead distribution pattern suggests a local source for the contamination of Valois Bay, and in fact a municipal sewer empties into the bay (Keighan, 1977; Malo and Gouin, 1977). The distribution pattern also suggests a link between contamination of Anse au Sable and input from the Vaudreuil channel.

Cadmium contamination was detected throughout Lake St. Louis; median was 8 μg/g and all values were high (Figure 25). Minimum and maximum concentrations were 2 μg/g and 19 μg/g respectively; maximum concentration was detected in Valois Bay. The four known sources of cadmium are upstream St. Lawrence River reaches and three industrial plants. One plant discharges effluent to the St. Charles River, a second discharges effluent to the Beauharnois Canal and the third discharges effluent to the southeast part of Lake St. Louis (Malo and Gouin, 1977; Keighan, 1977; Asseau, 1989).

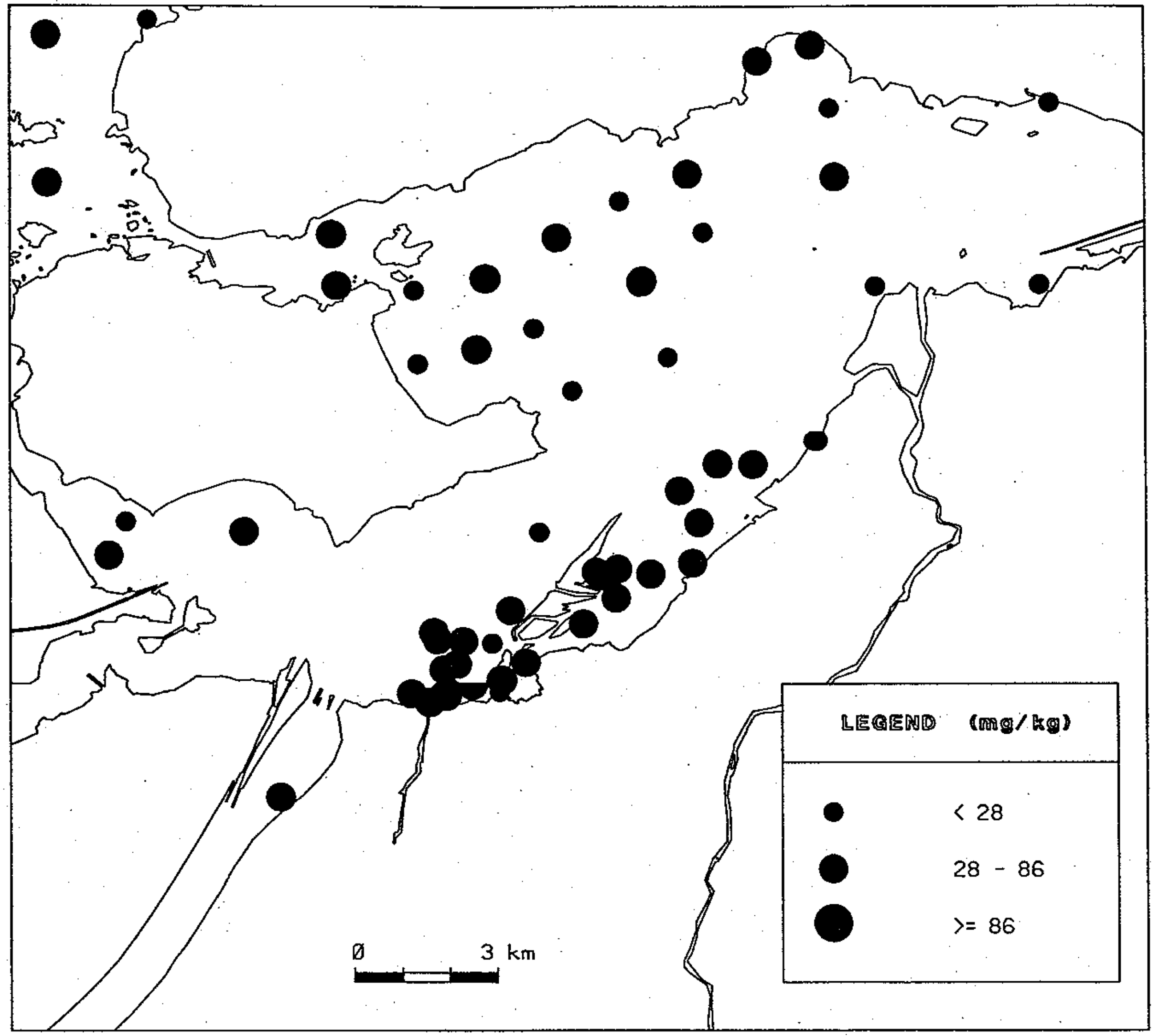


Figure 22 Copper distribution in Lake St. Louis sediment (1976)

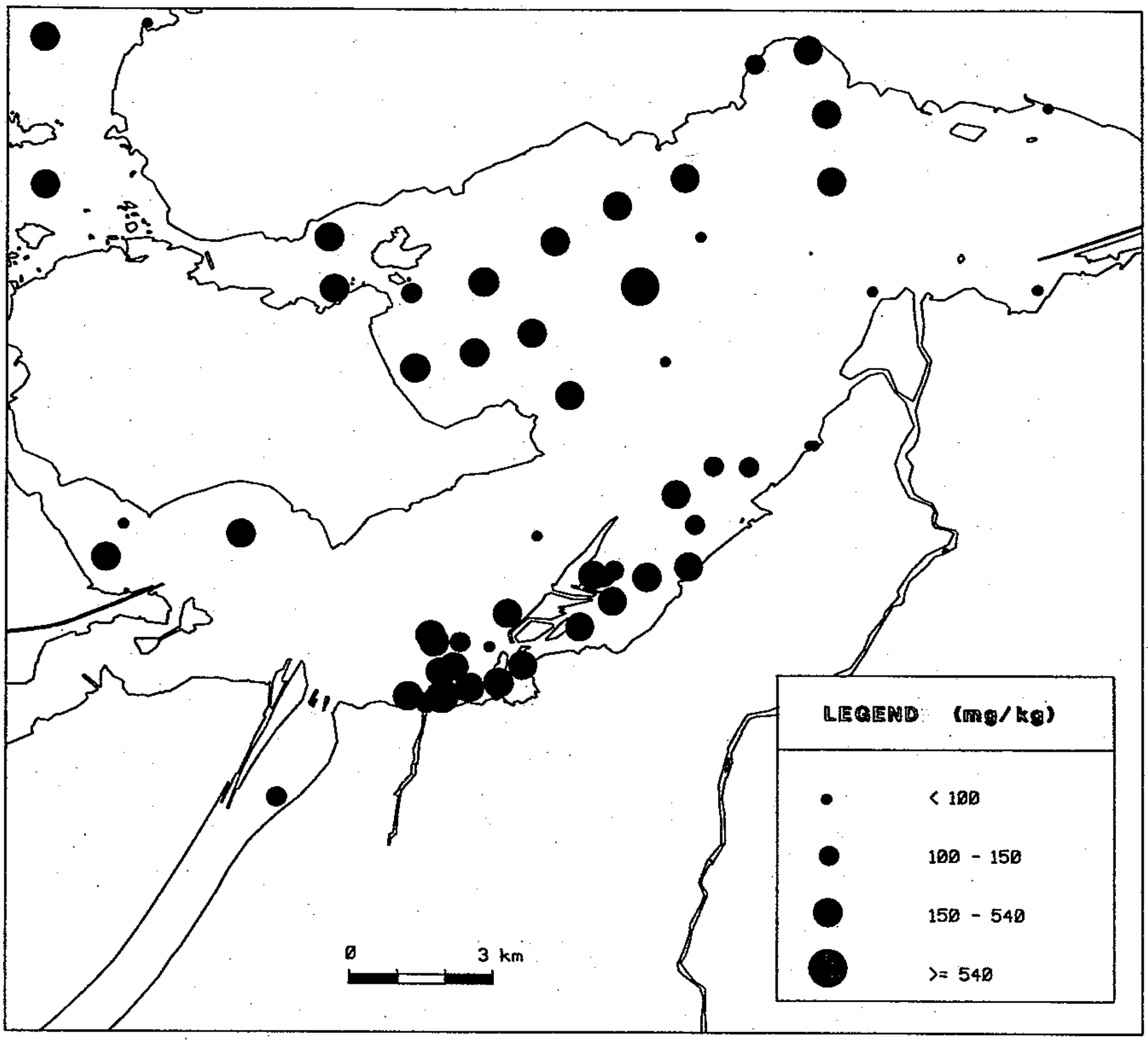


Figure 23 Zinc distribution in Lake St. Louis sediment (1976)

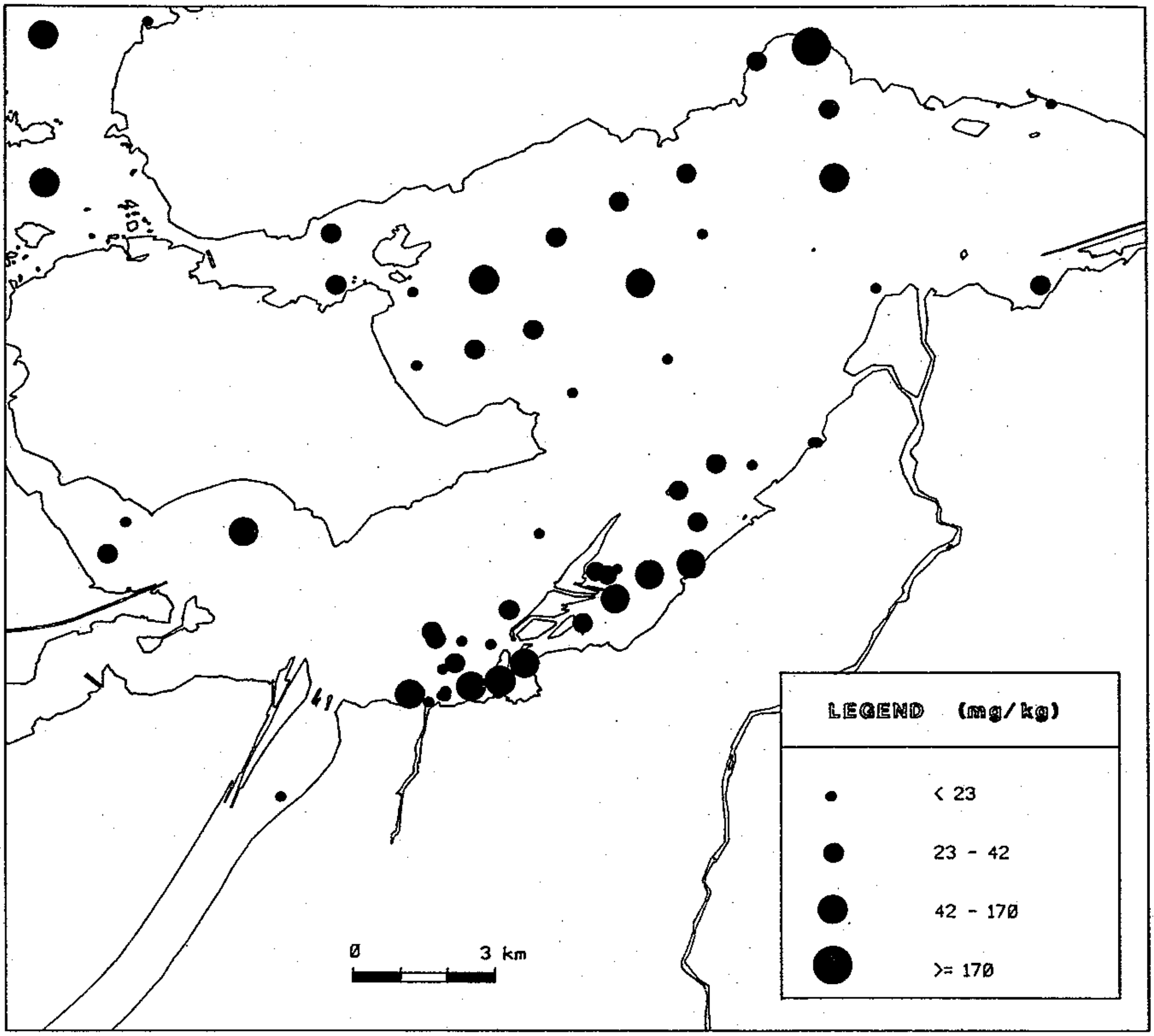


Figure 24 Lead distribution in Lake St. Louis sediment (1976)

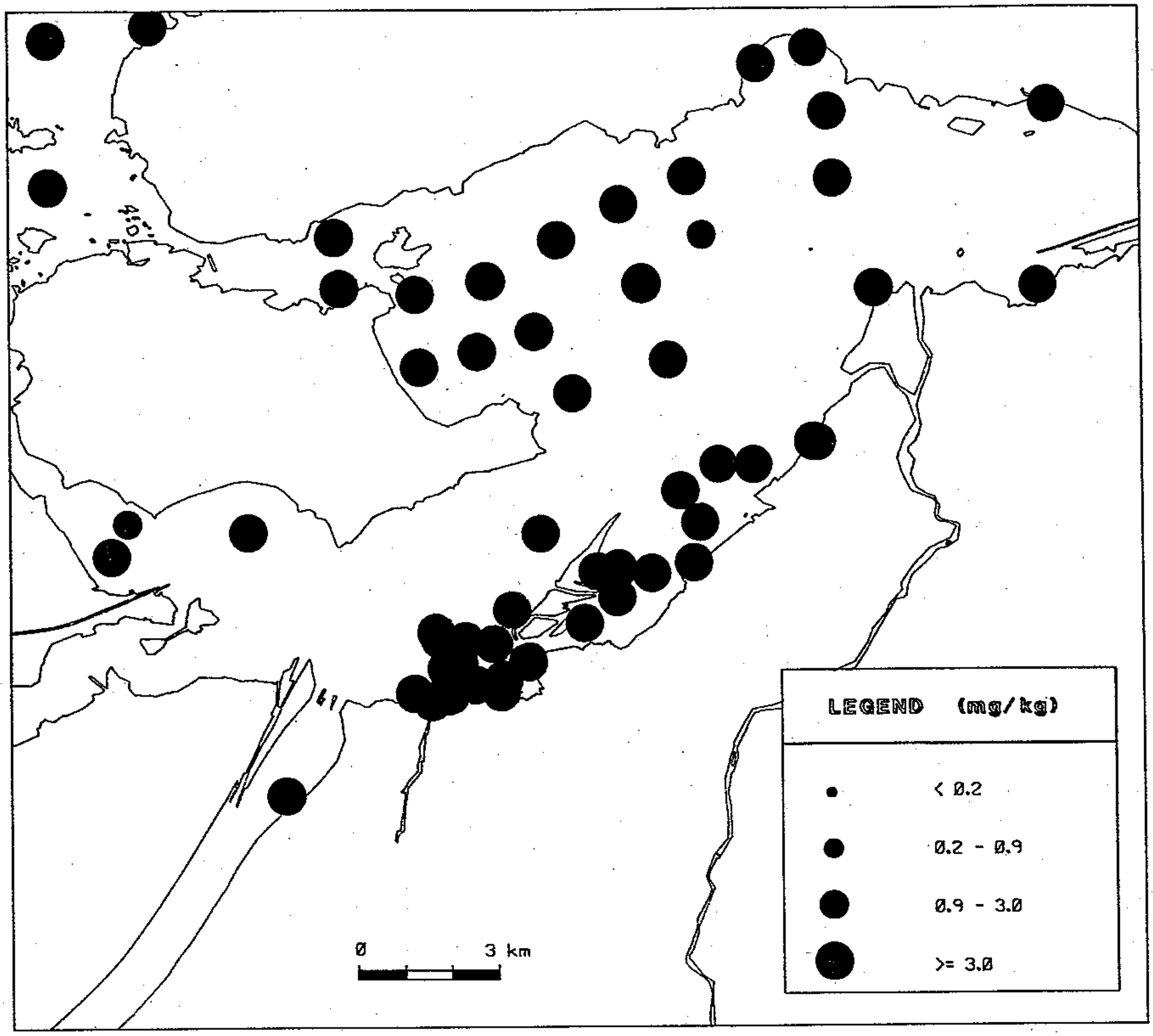


Figure 25 ***Cadmium distribution in Lake St. Louis sediment (1976)***

Median concentration of chromium in Lake St. Louis is moderate (68.4 μg/g). All zones identified in Table 20 with the exception of the centre of the lake are moderately contaminated (Figure 26). Highest medians were in Valois Bay, the St. Louis River and Anse au Sable, in that order. Keighan (1977) as well as Malo and Gouin (1977) identified the Valois Bay sanitary and storm sewers on the north shore and an industrial plant in the Beauharnois region on the south shore as major local sources of contamination.

Nickel contamination of Lake St. Louis was on the whole similar to chromium contamination (Figure 27). Median concentration (41.1 μg/g) was moderate; with the exception of the lake centre and the Beaconsfield area, the six zones sampled proved moderately contaminated. High nickel concentrations were detected in spots southeast of Îles de la Paix (88 μg/g), in the St. Louis River (81.2 μg/g) and in Anse au Sable (62.8 μg/g).

Contamination trends between 1976 and 1984-1985 were determined using basic data from an intensive sediment survey conducted in 1984 and 1985.

Although a drop in mercury levels was noted (median dropped from 0.73 μg/g in 1976 to 0.42 μg/g in 1984-1985), sediment remained seriously contaminated in certain areas (Figure 28). The mouth of the St. Louis River seems to have recovered: median concentration dropped from 3.48 μg/g in 1976 to 1.38 μg/g in 1984-1985, and maximum concentration also dropped significantly (from 86.92 μg/g in 1976 to 34.9 μg/g in 1984-1985). Despite the recovery, the area remains highly contaminated by mercury (Figure 29). Mercury contamination of sediment southeast of Îles de la Paix also decreased on the whole (median dropped from 0.81 μg/g in 1976 to 0.54 μg/g in 1984-1985), but the area still remained moderately contaminated. Improvements in this part of the lake stem from the significant decrease in mercury discharges to the St. Louis and the St. Lawrence rivers by plants in the Beauharnois region. Industrial discharges of mercury dropped from 1 987 kg/a in 1967 (Sturton, 1970, in Sérodes and Talbot, 1978) to about 20 kg/a in 1989 (Asseau, 1992b).

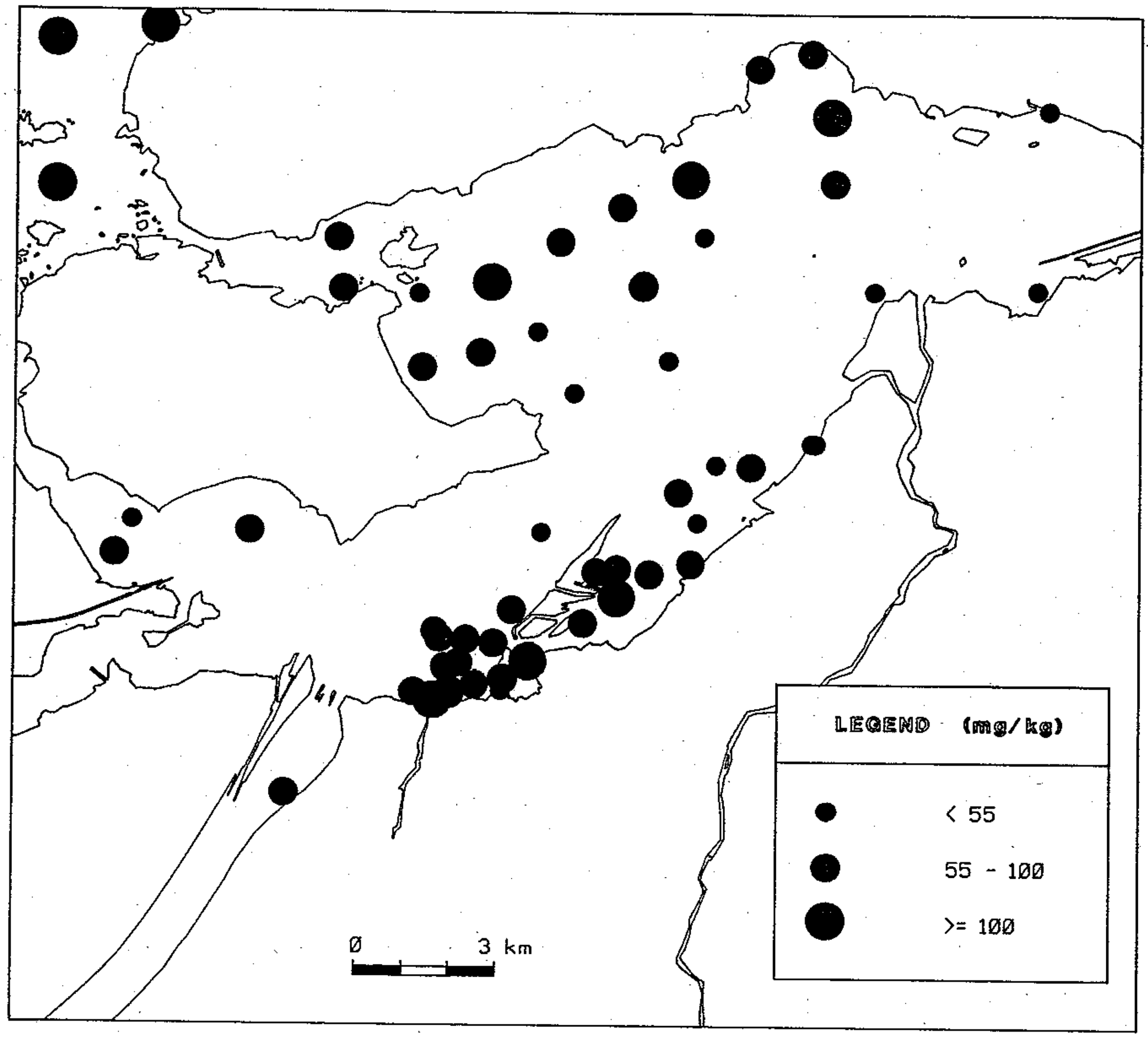


Figure 26 ***Chromium distribution in Lake St. Louis sediment (1976)***

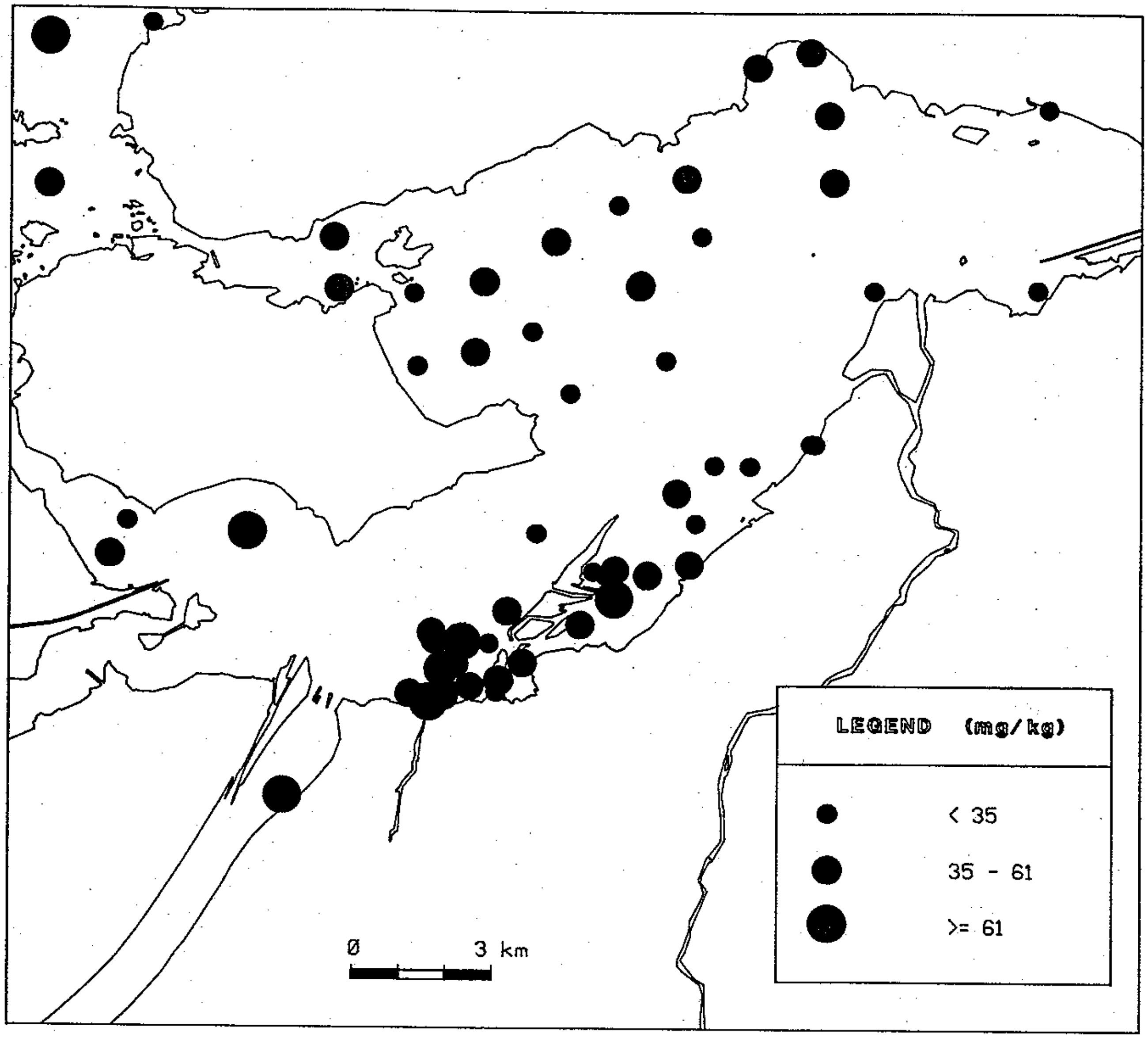


Figure 27 ***Nickel distribution in Lake St. Louis sediment (1976)***

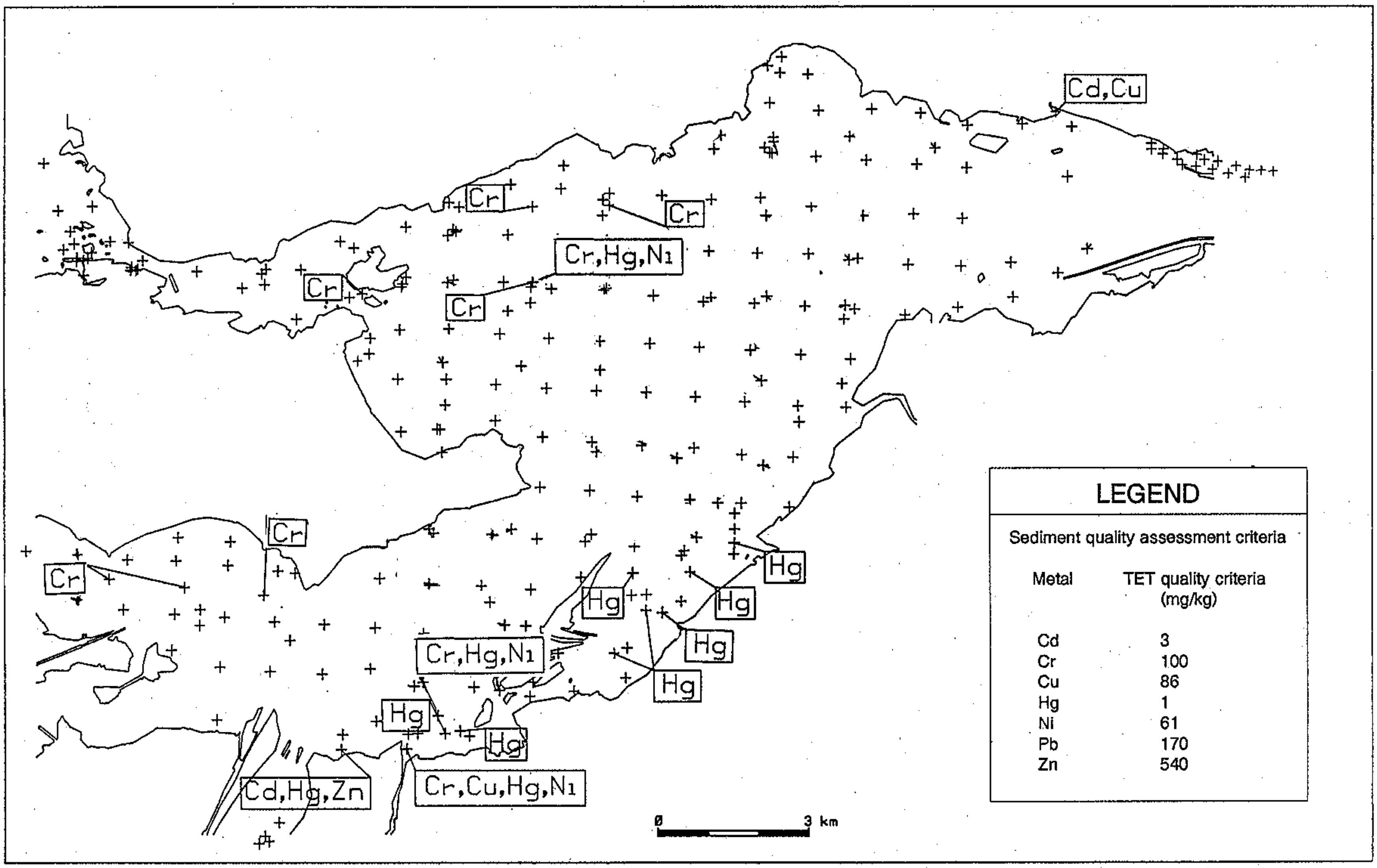


Figure 28 ***Exceedences of TET quality criteria in Lake St. Louis (1984-1985)***

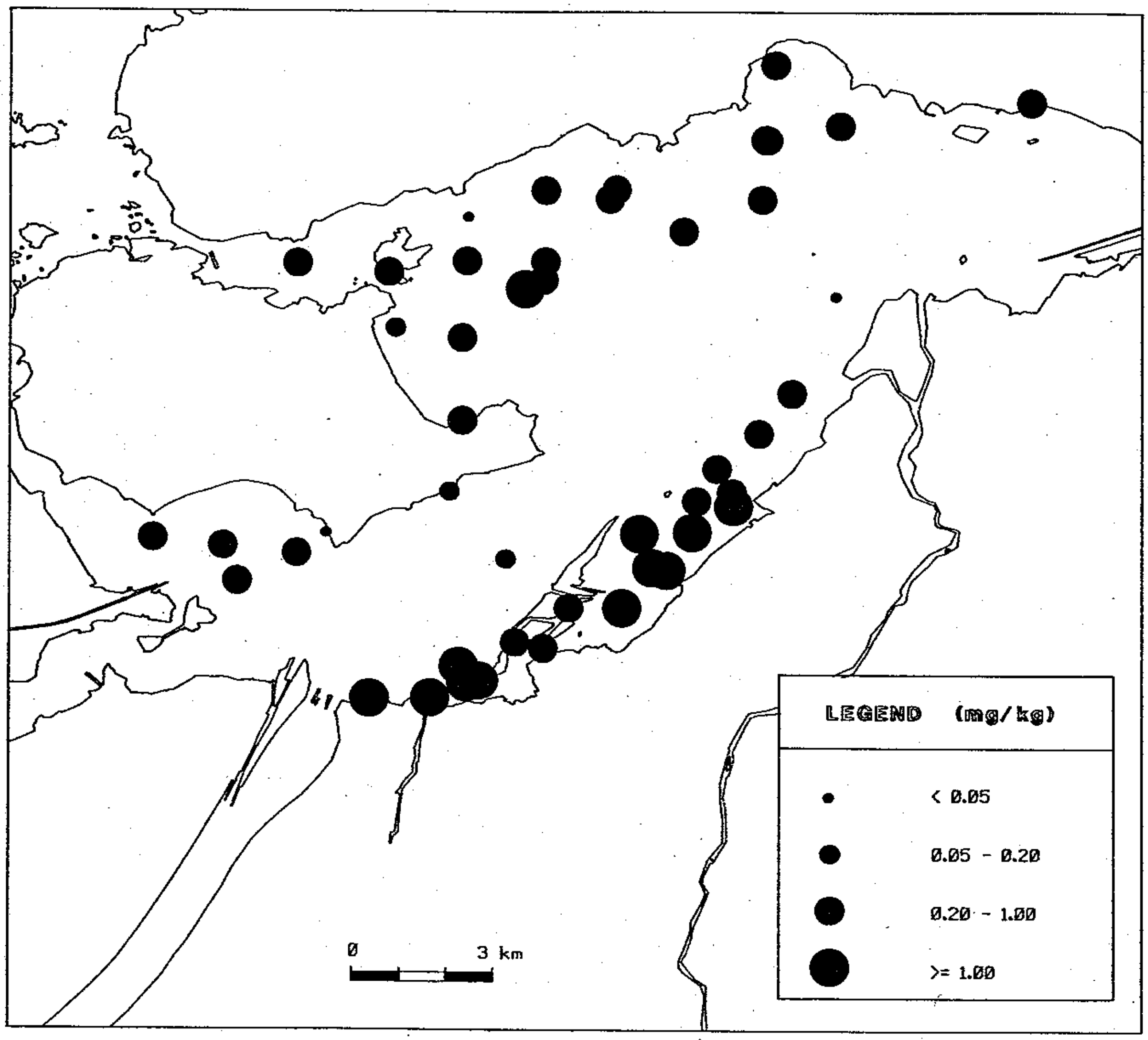


Figure 29 *Mercury distribution in Lake St. Louis sediment (1984-1985)*

An appreciable decrease in mercury contamination was also noted in Valois Bay and the lake centre, though high levels were still detected in spots. This was confirmed by a Montréal Urban Community survey in 1986-1987 (MUC, 1988).

Mercury contamination was also noted in Anse au Sable and in areas poorly sampled in 1976, including the Vaudreuil outlet, the area north of Dowker Island and the Beaconsfield lakeshore. High concentrations were detected during local surveys conducted by Champoux and Sloterdijk (1988) and by the MUC (1988). These high concentrations derive from Ottawa River input and discharges from local outfalls. As in 1976, only slight contamination was detected in the seaway channel in 1984-1985.

On the whole, copper contamination of Lake St. Louis in 1984-1985 (median of 35 μg/g) was comparable to copper contamination of the lake in 1976 (median of 37.2 μg/g). In some parts of the lake, median dropped: at the mouth of the St. Louis River, southeast of Îles de la Paix and in Valois Bay (Figure 30). Copper enrichment of the lake in 1984-195 was comparable to copper enrichment of the lake in 1976. Median copper concentration did however increase at Beaconsfield and in Anse au Sable. High copper levels were detected downstream of the Vaudreuil and Ste. Anne outlets and in Valois Bay.

Given the pattern of contamination, the source appears to be local municipal outfalls and the Ottawa River via the Vaudreuil and Ste. Anne channels: close to 50 t/a of copper were transported by the channels, and municipal outfalls discharged another 0.5 t/a (Asseau 1992b).[3] Estimated copper input from upstream reaches of the St. Lawrence (260 t/a) may explain the contamination in the centre of the lake and partially explain that southeast of Îles de la Paix. Copper input from industrial plants in the Beauharnois area (0.8 t/a) and from the St. Louis River (0.2 t/a) was still detected in 1989, but it was low compared to that from other sources; concentrations detected suggest much less input in 1984-1985 than a decade earlier.

---

3. This is an underestimate of municipal discharges around 1985 because it does not include discharges from Montreal Island municipalities connected to the north collector at the time of Asseau's 1989 estimate.

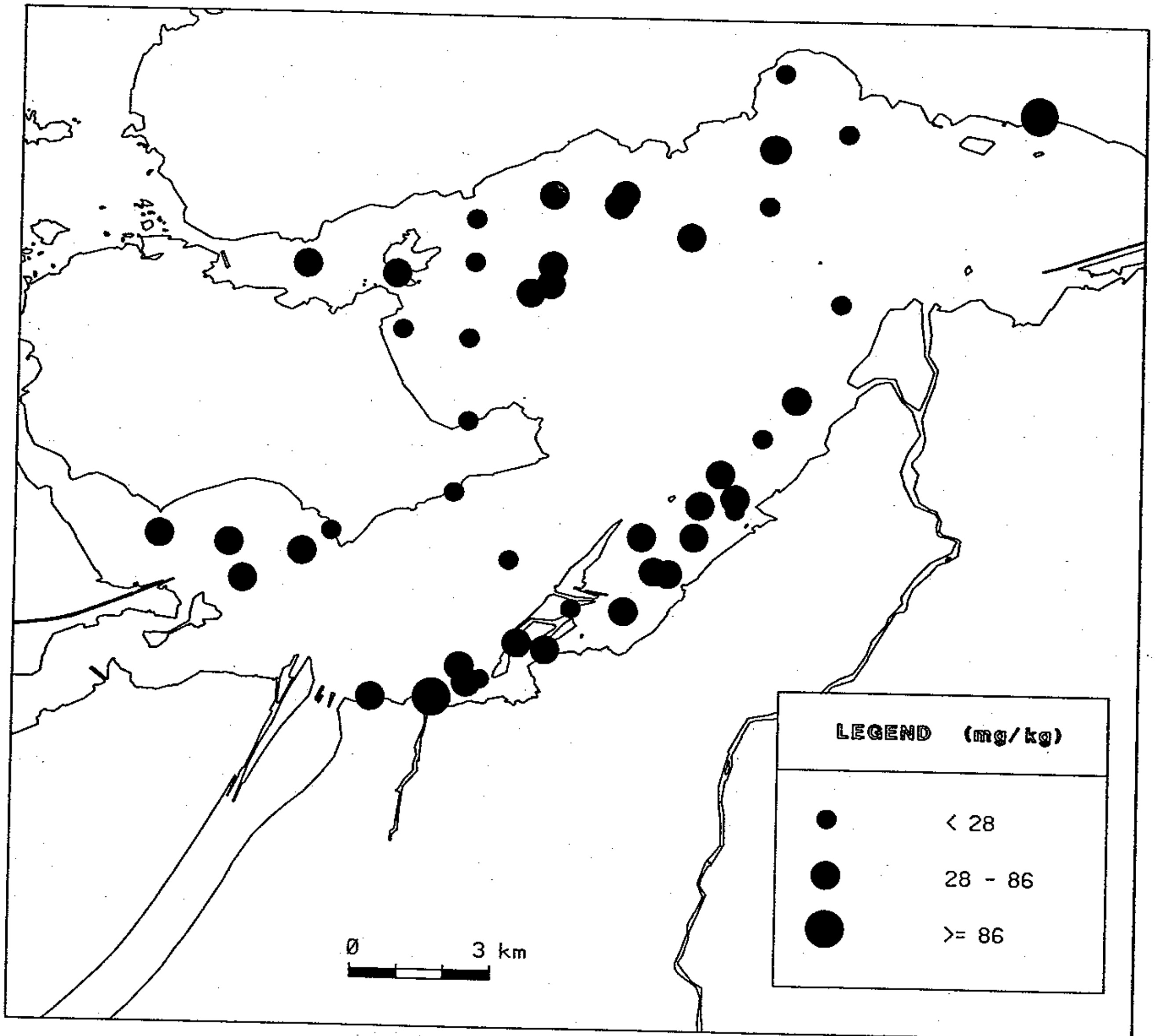


Figure 30 **Copper distribution in Lake St. Louis sediment (1984-1985)**

Input from the Châteauguay River (detected in the lesser La Prairie basin) was low (5 t/a). There is not enough environment characterization data to determine the impact of Châteauguay River input on sediment at the mouth of the river.

Zinc levels were generally about the same in 1984-1985 as in 1976 (1976 median was 176 µg/g and 1984-1985 median was 179 µg/g). Differences were however noted in particular areas: levels dropped at the mouth of the St. Louis River and in the centre of the lake, remained the same around Îles de la Paix and increased around Beaconsfield, in Valois Bay and in Anse au Sable (Figure 31). The Dowker Island basin was sampled in 1984-1985 and proved to be highly contaminated; zinc concentrations were higher here (686 µg/g) than anywhere else in Lake St. Louis. The most contaminated areas, apart from the Dowker Island basin, were the Beaconsfield area, Valois Bay and Anse au Sable.

The pattern of contamination highlights the major role played by Montréal Island sources[4] and Ottawa River input (via the Ste. Anne channel) in local contamination; input from these sources was estimated at 40 t/a (Asseau, 1992). Upstream reaches of the St. Lawrence River are the major source of zinc (920 t/a) and contribute to contamination of the centre of the lake and Îles de la Paix. Much of the toxic input, however, only passes through Lake St. Louis. Ottawa River input via the Vaudreuil channel (310 t/a) undoubtedly plays an active role in deterioration of Anse au Sable. Châteauguay River input (11 t/a) contributes mainly to contamination of the lesser La Prairie basin. The St. Louis River (0.4 t/a) and the industrial plants of the Beauharnois area (3 t/a) undoubtedly contribute less to local zinc contamination than they did a decade earlier, judging by sediment quality, but they are still sources of contamination.

4. In 1984-1985, the Montreal Urban Community's north collector was not yet operational. Municipal waste from the Montreal West Island discharged directly to Lake St. Louis.

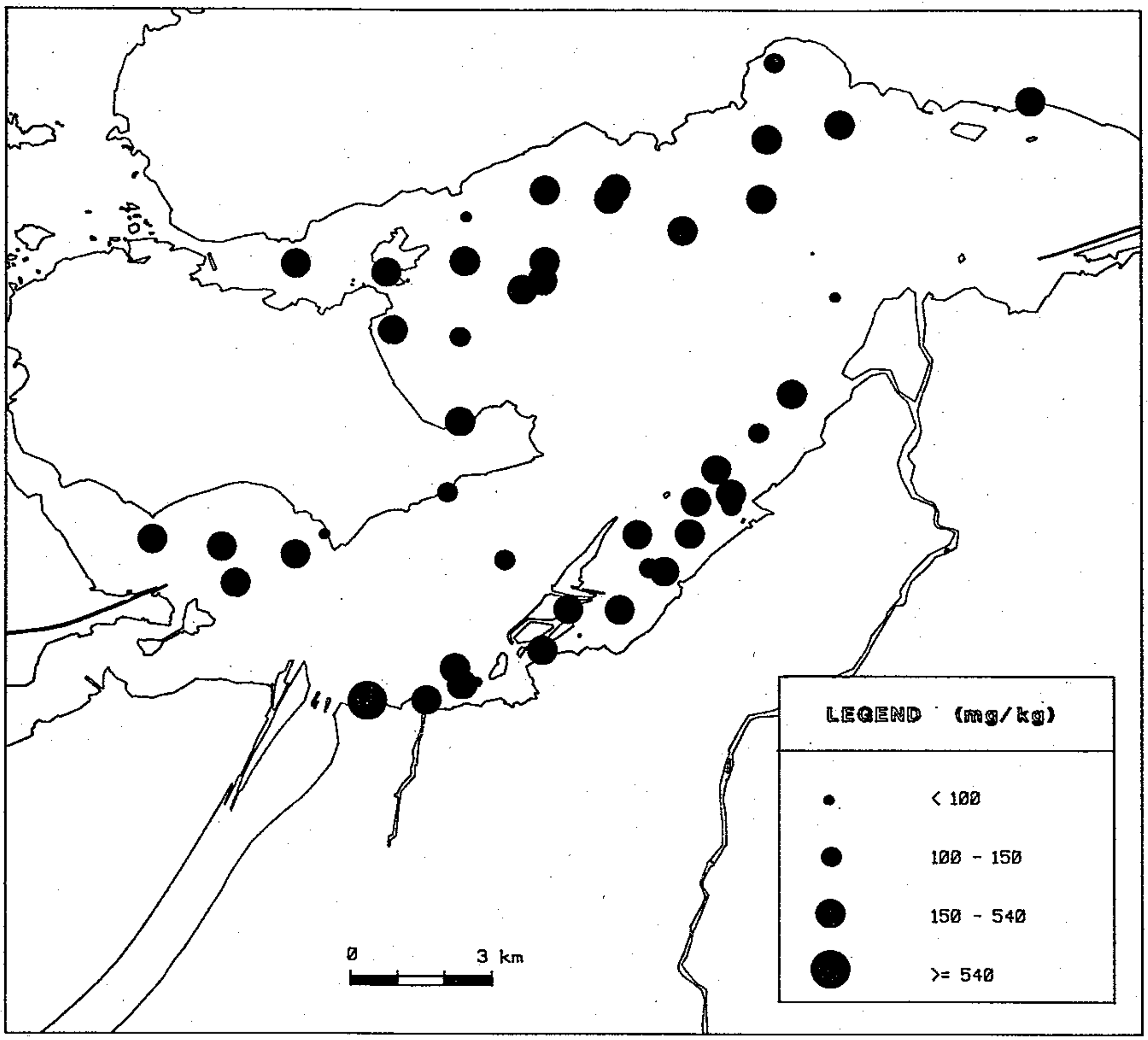


Figure 31 ***Zinc distribution in Lake St. Louis sediment (1984-1985)***

Lead contamination of Lake St. Louis increased slightly over the decade: median was 36 μg/g in 1984-1985 compared to 23 μg/g in 1976. Sediment quality was slightly worse in all contaminated areas of the lake in 1984-1985; contamination was moderate. In 1984-1985, highest lead concentrations were detected around Beaconsfield, in Valois Bay and in Anse au Sable (Figure 32). Here too, contamination seemed to stem from Montréal West Island outfalls and Ottawa River input (estimated at 24 t/a, Asseau, 1992b). The influence of the Châteauguay River, the major source of lead in Lake St. Louis (70 t/a), was noted in the lesser La Prairie basin. Input from upstream reaches of the St. Lawrence River (58 t/a) may be responsible for contamination of the central part of the lake. Industrial discharges (3.3 t/a) seem the main source of contamination of the mouth of the St. Louis River.

Surface sediment was much less contaminated by cadmium in 1984-1985 than in 1976. Median for Lake St. Louis as a whole dropped from 8 μg/g in 1976 to 1 μg/g in 1984-1985, and similar decreases were noted in all contaminated areas of the lake (Figure 33). Contamination was moderate. It is difficult to pinpoint sources of cadmium contamination because of the dispersion of the contaminant, but input seems to have decreased appreciably.

Median concentrations of chromium were moderate during both survey periods (68.4 μg/g in 1976 and 72 μg/g in 1984-1985). Pattern of chromium spatial distribution was somewhat different in 1984-1985 however; median concentrations were slightly higher than in 1976 in the Beaconsfield area and in Anse au Sable, slightly lower in Valois Bay (Figure 34), and stable at the mouth of the St. Louis River, around Îles de la Paix and in the centre of the lake. Highest medians were recorded in Anse au Sable and in the Beaconsfield area. This pattern of distribution suggests the Ottawa River and Montréal Island municipal discharges play a major role in chromium contamination. The pattern of distribution also suggests input from upstream reaches of the St. Lawrence River, from the St. Louis River and from industrial plants south of Lake St. Louis remained stable over the decade.

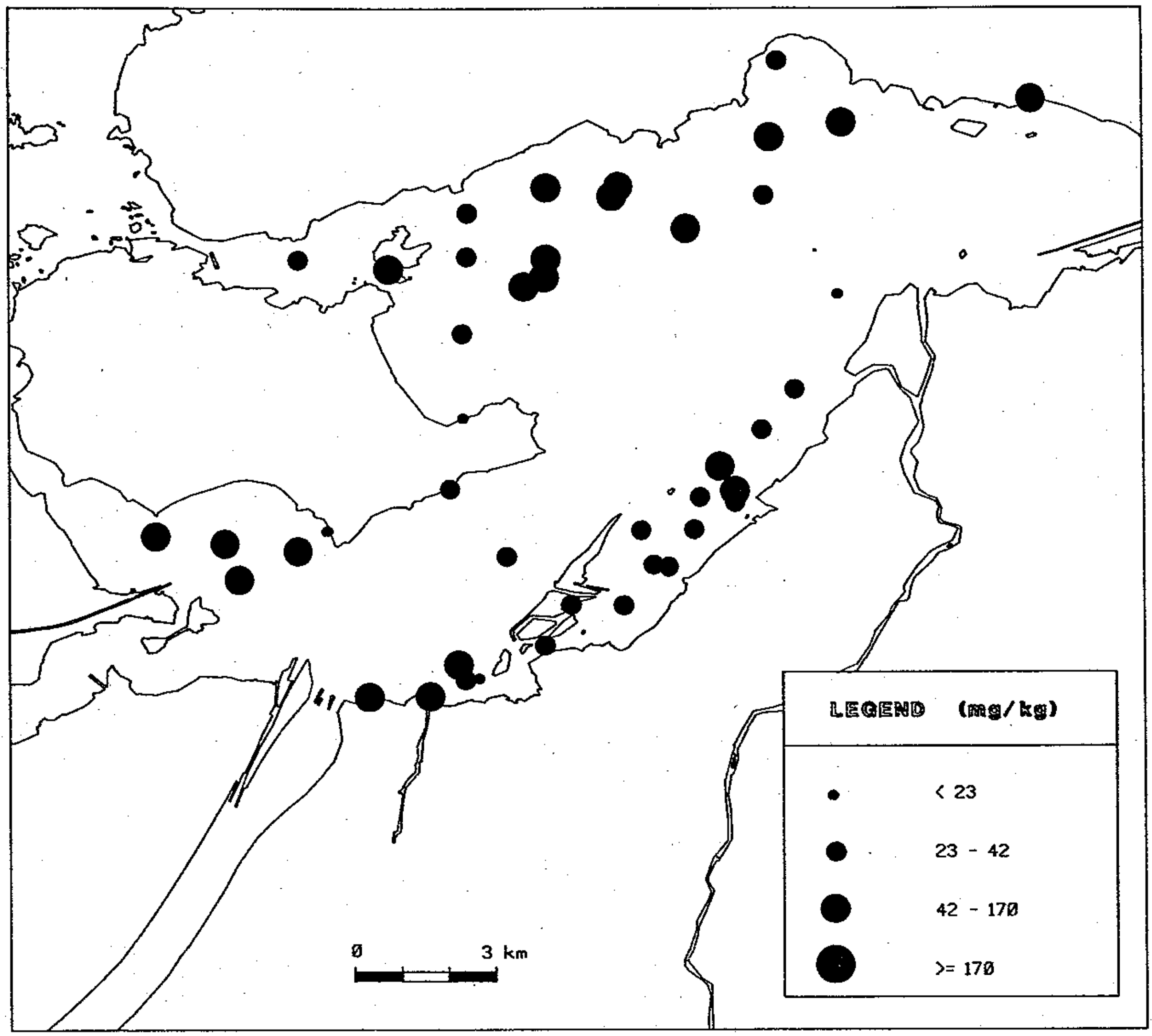


Figure 32 Lead distribution in Lake St. Louis sediment (1984-1985)

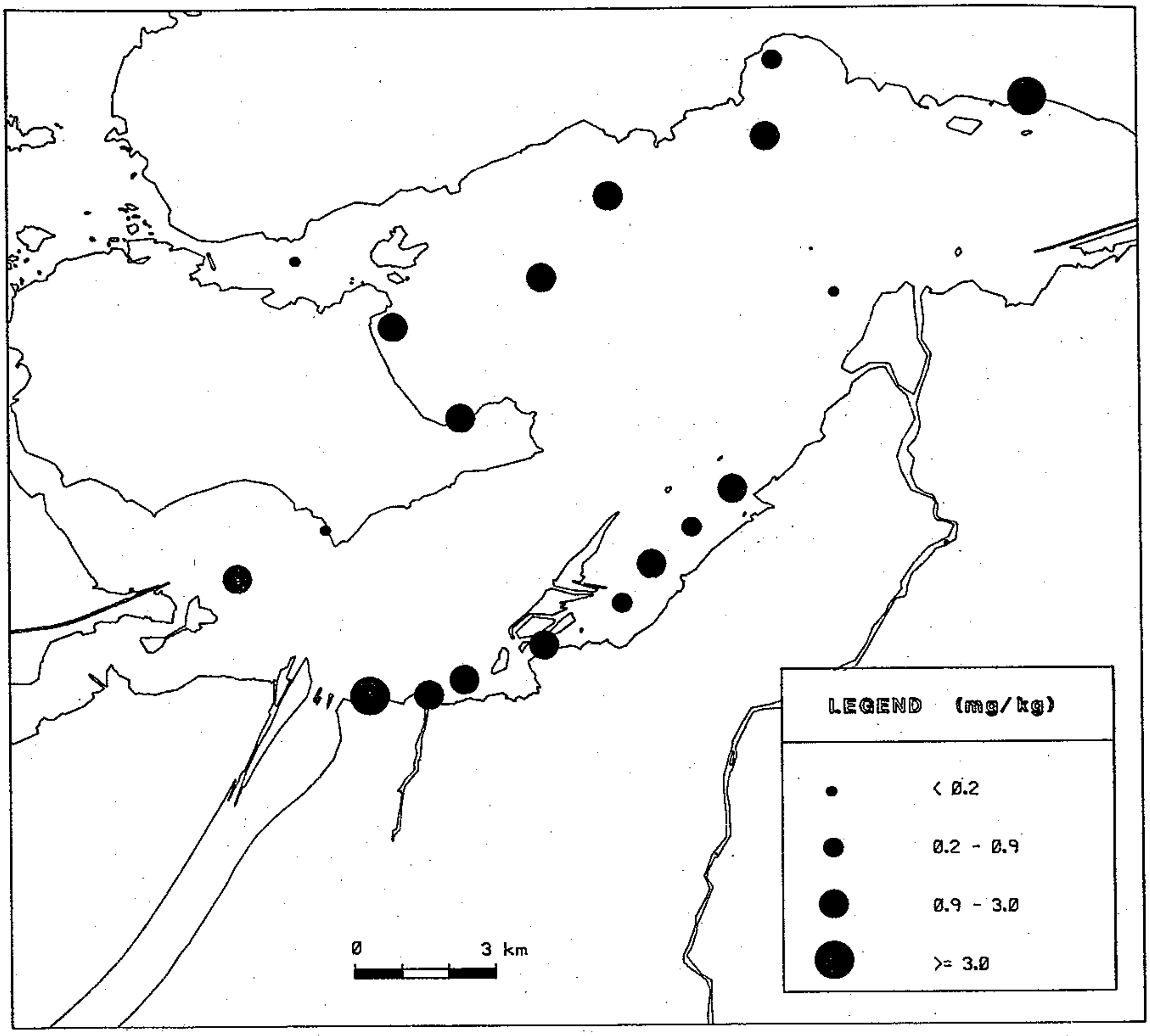


Figure 33 Cadmium distribution in Lake St. Louis sediment (1984-1985)

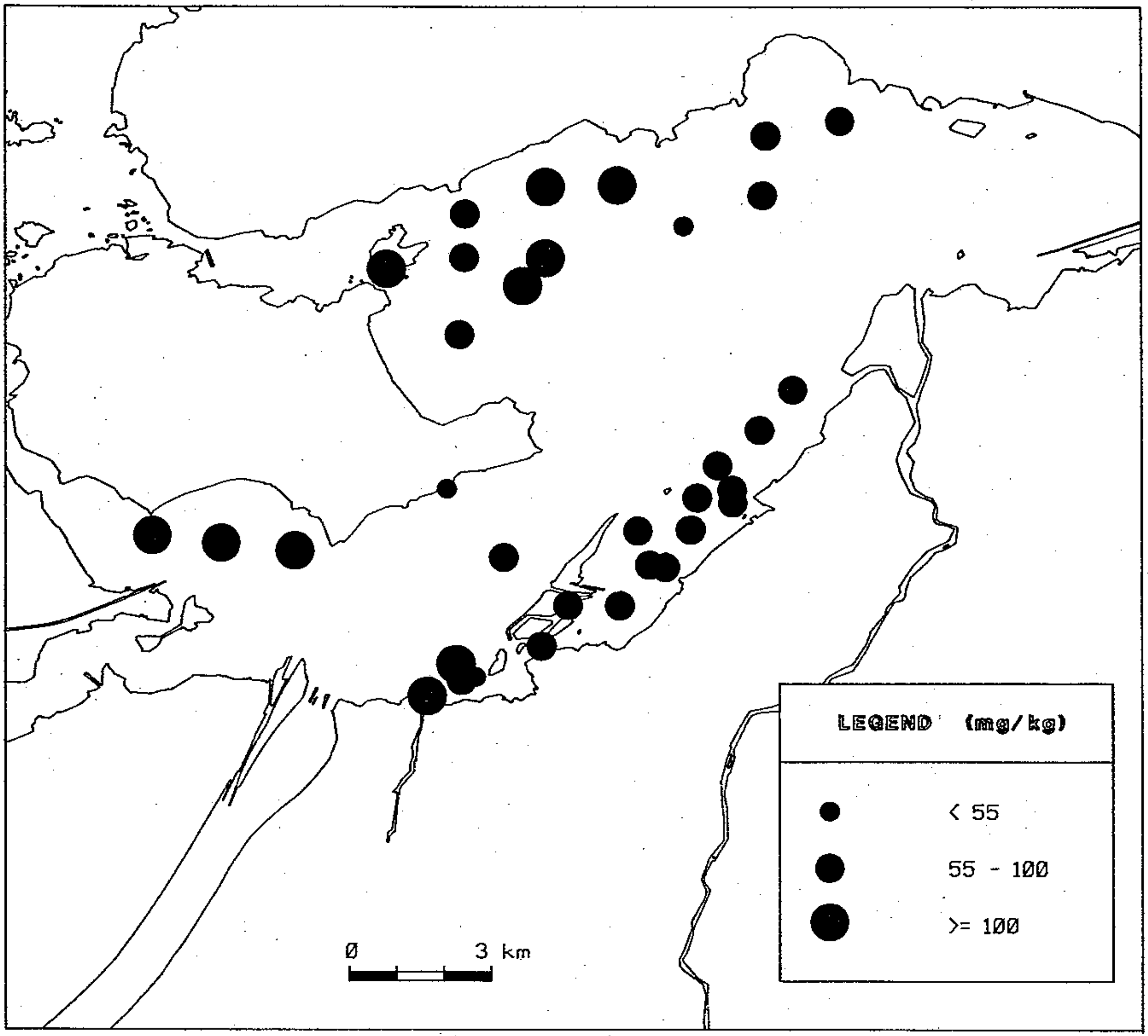


Figure 34 Chromium distribution in Lake St. Louis sediment (1984-1985)

Nickel concentrations were on the whole slightly lower in 1984-1985 than in 1976 (median was 41.1 μg/g in 1976 compared to 35 μg/g in 1984-1985); contamination was moderate. A decrease was noted in a number of areas, but in Anse au Sable and the central part of the lake nickel concentrations remained stable and in Beaconsfield they increased slightly (Figure 35). Highest medians were in Anse au Sable, in the Beaconsfield area and at the mouth of the St. Louis River. Maximum concentration was at the mouth of the St. Louis River (77 μg/g).

Conclusion. On the whole, sediment quality improved in Lake St. Louis between 1976 and 1985. The mouth of the St. Louis River was the most contaminated area in the lake in 1976, yet the 1984-1985 data show the biggest improvement over the decade was in this area; contamination by mercury, copper, zinc, cadmium and nickel decreased. With the reduction in industrial discharges to the Beauharnois region, some loads decreased significantly--mercury load in particular. The area was still nonetheless very contaminated by mercury in 1984-1985.

Sediment quality also improved south of Îles de la Paix over the decade. Mercury, cadmium and nickel contamination decreased. Concentrations of the other heavy metals remained stable in this area. The area is affected by industrial discharges from the Beauharnois region and input from upstream St. Lawrence River reaches. The data collected suggest the decrease in discharges at Beauharnois did not affect sediment quality as much in this area as at the mouth of the St. Louis River.

Sediment quality improved slightly in the centre of the lake over the decade. Mercury, zinc and cadmium contamination decreased. Concentrations of the other metals remained stable or increased slightly (lead). This area is affected by waters from upstream reaches of the St. Lawrence River, which transport loads from subsystem 1, and by waters of the Ottawa River, also loaded with contaminants. Only some of the toxic load sinks, however; the rest is transported downstream.

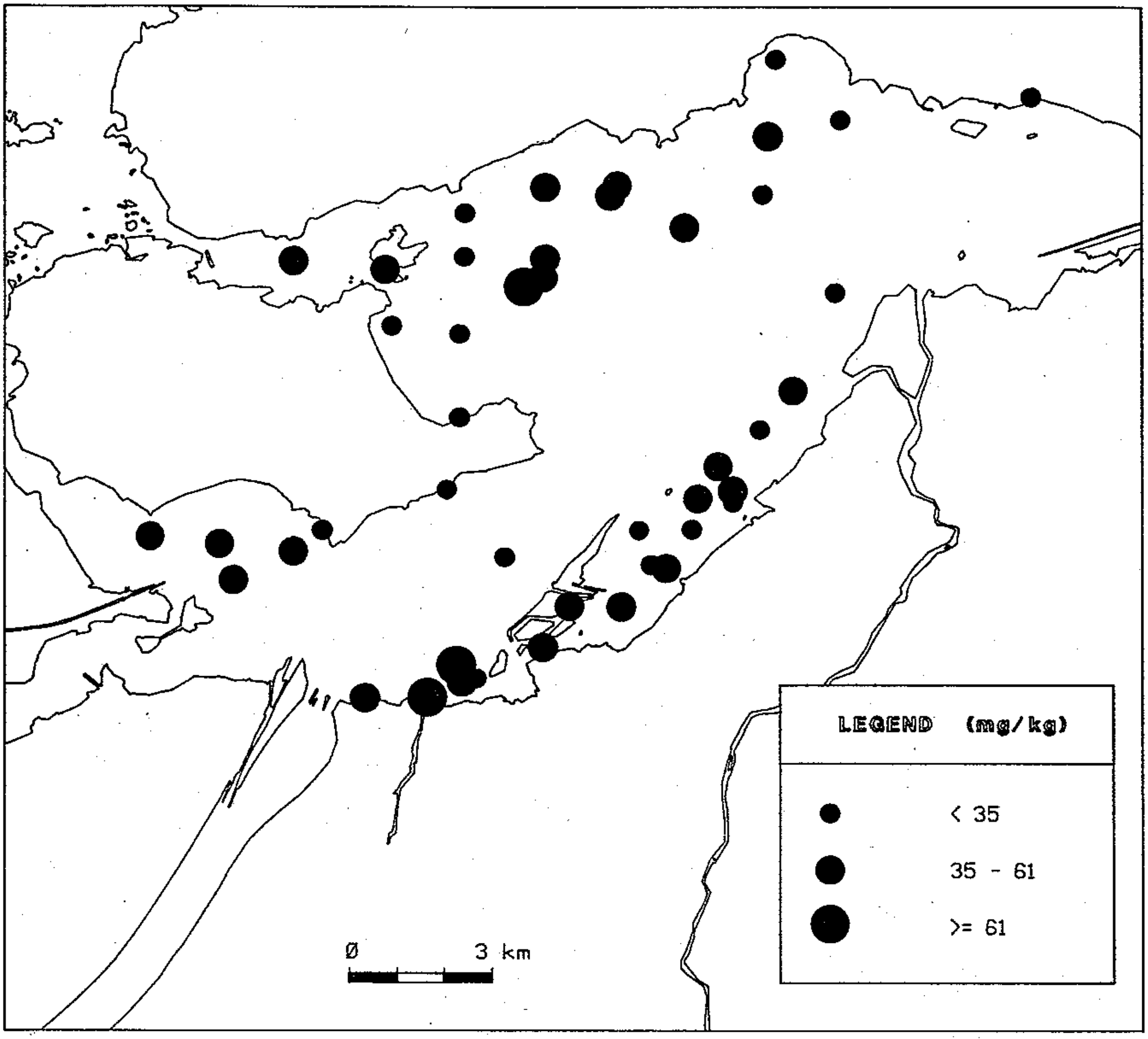


Figure 35 Nickel distribution in Lake St. Louis sediment (1984-1985)

Sediment quality also improved in Valois Bay over the decade. Median concentrations of mercury, copper, cadmium, chromium and nickel decreased. Median concentrations of lead and zinc increased however. The contamination is essentially attributable to discharges from Montréal West Island outfalls and to Ottawa River input.

Data collected around Beaconsfield, north of Dowker Island and at the Ste. Anne channel outlet between 1984 and 1987 showed serious or moderate contamination by mercury, copper, zinc, lead and chromium. The contamination may be due to Montréal West Island municipal discharges as well as Ottawa River input. Champoux and Sloterdijk analyzed the geochemical composition of the sediment in these sedimentation zones and concluded it comes from the Ottawa River (Champoux and Sloterdijk, 1988).

Sediment in the Vaudreuil channel is contaminated by mercury, copper, zinc and lead. Champoux and Sloterdijk concluded the sediment in these sedimentation zones also comes from the Ottawa River (Champoux and Sloterdijk, 1988).

4.3 Subsystem 2b: The La Prairie basin to Pointe du Lac

4.3.1 Physiography and dynamics. This stretch of the St. Lawrence River (between the Lake St. Louis outlet and Pointe du Lac) is 120 km long. Upstream to downstream the main components of the subsystem are the two La Prairie basins (a single basin before construction of the St. Lawrence Seaway), a river corridor dotted with archipelagos (Boucherville, Varennes, Verchères and Contrecoeur), a delta (Sorel) and a major widening (Lake St. Pierre) (Figures 36 and 37).

The La Prairie basin divides into two hydrodynamically and sedimentologically very different parts. The northern part of the basin (the greater La Prairie basin) has not been altered much by man. Upstream, the greater La Prairie basin is a narrow set of fast-dropping rapids (the Lachine rapids). The rapids are followed by a shallow widening where current remains fast. The greater La Prairie basin receives most of the discharge from Lake St. Louis, with its distinct green and brown water masses.

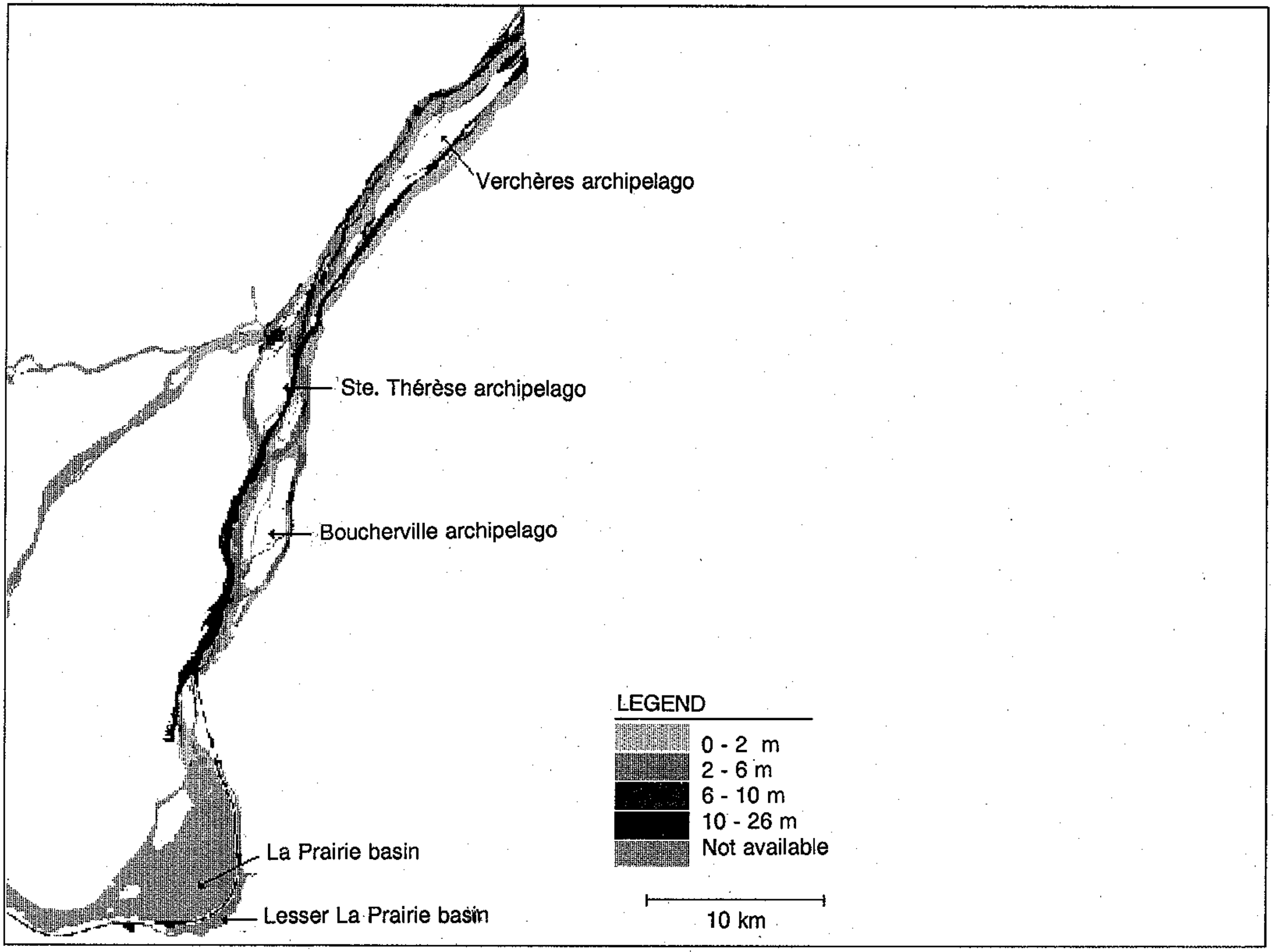


Figure 36 ***Bathymetry between the La Prairie basin and the Sorel delta***

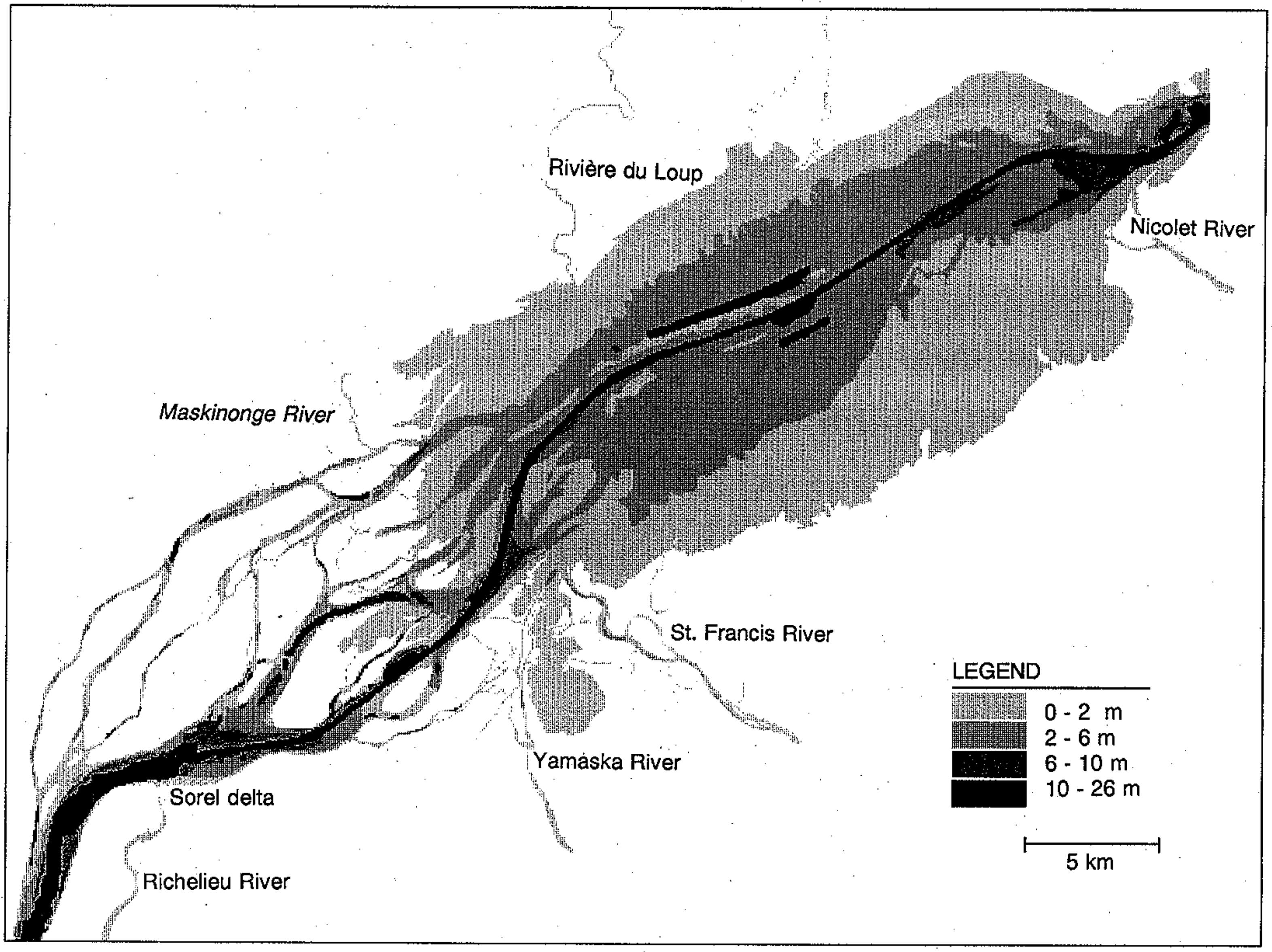


Figure 37 Bathymetry of Lake St. Pierre

The southern part of the basin was diked about forty years ago to create a shipping channel; this is the lesser La Prairie basin. Velocities are slow here, inflows are small and sedimentation is active. Flow is controlled at both ends of the basin to facilitate passage of commercial ships. Water level is maintained at elevation 11.5 m from April to December and then dropped several metres from January to March so the locks and seaway channel can be maintained when there is no shipping traffic. The lesser La Praire basin receives the waters of the Châteauguay and St. Louis rivers as well as some of the green waters of the upstream reaches of the St. Lawrence River.

Between the La Prairie basin outlet and the eastern tip of Montréal Island, the waters run through a narrow corridor dotted with rapids and islands. The northern part of the corridor was deepened to 10.7 m for passage and docking of commercial ships. Currents are especially fast around St. Helen's Island and in the shipping channel. In addition, most of the discharge of the St. Lawrence River runs through this channel. There are deposition areas near docks, in areas protected by islands and along parts of the shoreline.

The corridor is similar between Repentigny and Tracy. Most of the flow runs through the shipping channel, where the water is at least 10.7 m deep and currents are fast. There are shallow areas with slower currents along the shoreline and in the archipelagos.

Many islands in the corridor are highly exposed to wind-generated waves, ice and lapping and are eroding at a rapid rate (Argus, 1991). As a result, large quantities of fine material are suspended and transported with the passage of high-speed ships, during storms and with ice drift.

Hydrodynamic conditions are very different starting at Sorel. The Sorel delta is a major sink. Most of the flow is directed into the seaway by a series of sills between the islands; the channels receive only a small portion of the flow. As a result, currents are much slower in Lake St. Pierre, and sediment accumulates. The channels are generally shallow (< 3 m) and densely covered with weedbeds.

Lake St. Pierre, the third natural widening in the Québec part of the St. Lawrence River, is an average 12 km wide and covers 400 km^2 (Hardy et al., 1991b).

It is an elongated, shallow body of water generally no more than 3 m deep--except in the seaway channel, where depth is maintained at 10.7 m by dredging. The bathymetry of Lake St. Pierre is simple, unlike that of Lake St. Francis or Lake St. Louis. Vast weedbeds colonize the shoreline, which slopes gently down on both sides of the lake to the bottom of the basin 3.5 m below. There are a few shallows in the upstream part of the lake south of the shipping channel and a major depression at the lake outlet. The seaway channel cuts longitudinally through the centre of the lake and receives most of the flow. There are no large islands downstream of the Sorel delta apart from Île aux Sternes (created from dredged material), but a few small artificial islands have been built to maintain the ice cover.

Vertical drop between Lake St. Louis and Lake St. Pierre (a distance of 120 km) is 17.3 m. The Lachine rapids are responsible for much of the drop; water level at Pointe aux Trembles is not much higher than at Lake St. Pierre (5.0 m compared to 3.4 m in the centre of Lake St. Pierre). Residence time in Lake St. Pierre is 20 h.

Mean annual discharge of the St. Lawrence River is 9 047 m^3/s at LaSalle, 149 m^3/s at the lesser La Prairie basin entrance and 10 750 m^3/s at Sorel. Tables 22 and 23 show St. Lawrence River discharges at Sorel and tributary discharges between the Lake St. Louis outlet and Pointe du Lac.

The following tributaries empty into the lesser La Prairie basin: Rivière de la Tortue, the St. Jacques River and the St. Régis River. Rivière des Prairies, Rivière des Mille Îles and Rivière L'Assomption empty into the St. Lawrence between Montréal and Sorel. Lake St. Pierre has six main tributaries: the Richelieu, St. Francis and Nicolet rivers on the south shore and the Maskinonge River, Rivière du Loup and the Yamachiche River on the north shore. A series of smaller streams also empty into Lake St. Pierre.

Rivière des Prairies is the tributary with the largest discharge, contributing about half the total discharge from subsystem tributaries and more than 65 percent of the discharge from tributaries in the Montréal area. The Richelieu River comes next, contributing 18 percent of total tributary discharge. The Richelieu River is the largest tributary of Lake St. Pierre, contributing about half of total annual discharge from the

Table 22 ***Mean annual discharge of the St. Lawrence River at Sorel between 1980 and 1987 (Environment Canada, 1992)***

Year	Mean annual discharge (m^3/s)
1980	10 700
1981	10 900
1982	9 990
1983	10 700
1984	10 900
1985	10 900
1986	11 600
1987	10 300
Mean (1980-1987)	10 750

Table 23 ***Tributary discharges between the Lake St. Louis outlet and Pointe du Lac (Asseau, 1992b and 1992c)***

Tributary	Discharge (m^3/s)
St. Jacques River	2.9
Rivière de la Tortue	2.44
St. Régis River	1.5
Rivière des Mille Îles	217
Rivière des Prairies	1 188
Rivière L'Assomption	75
St. Francis River	222
Yamaska River	110
Richelieu River	410
Bayonne River	4.4
Maskinonge River	14
Rivière du Loup	20
TOTAL	2 267

lake's tributaries. Next come the St. Francis River and Rivière des Mille Îles, which have similar discharges, followed by the Yamaska River. The other tributaries make only a minor contribution to total subsystem flow.

Water quality is not homogeneous between La Prairie and Pointe du Lac; the waters divide into five distinct adjacent streamlines. Tributary waters run down along the shoreline and do not mix much because of the low shear of the different water masses, but they are nevertheless affected by bathymetry, velocities and flows.

The lesser La Prairie basin mainly receives waters of the St. Louis and Châteauguay rivers and of the basin's three tributaries. The waters of Rivière des Prairies, Rivière des Mille Îles and Rivière L'Assomption only mix with those from upstream reaches of the St. Lawrence River far from their confluence; streamline of these rivers is perceptible beyond Lake St. Pierre. Hydrotech (1989) describes water mixing in Lake St. Pierre as follows (our translation):

> Mixing of tributary waters begins almost immediately after the waters enter the lake and spreads rapidly. Waters in the lake are as follows:
>
> - In the centre of the lake are intact waters from the Great Lakes.
> - On the left side there is a partial mixing zone formed of waters from the Ottawa and Maskinonge rivers, Rivière du Loup, Rivière L'Assomption and upstream reaches of the St. Lawrence River.
> - On the right side, there is a mixing zone formed of waters of the Richelieu, St. Francis and Yamaska rivers and upstream reaches of the St. Lawrence River.
>
> Tributaries thus play a very important role in water quality at the bottom of Lake St. Pierre; because the lake is so shallow, tributary waters spread out into the lake from the shoreline.

With the exception of the Lachine rapids, current is fastest in the shipping channel, where velocities are always more than 0.6 m/s--except in Lake St. Pierre, where they are still nonetheless always more than 0.3 m/s (Hydrotech, 1989). During floods, velocities can reach 1.8 m/s in the channel and 1 m/s elsewhere in the lake. High velocities coupled with wind effect, waves and lapping cause substantial island erosion--espcially of islands bordering the shipping channel (Argus, 1991).

Close to the shoreline and in lacustrian areas, currents are slower (0.1 to 0.3 m/s). In well-sheltered areas such as bays, islands, harbours and marinas, velocities barely reach 0.1 m/s. Most sedimentation occurs in these areas (Hydrotech, 1989). Apart from the marinas and harbours, these are also the areas richest in weedbeds.

Solid input to the subsystem at the Lake St. Louis outlet is 2 600 000 t/a (8 to 10 mg/L).[5] Most of the load comes from tributaries in the province of Québec. Another 690 000 t/a are contributed between Montréal and Sorel by Rivière des Prairies, Rivière des Mille Îles, Rivière L'Assomption, La Chaloupe River and other smaller tributaries. Solid input at the Sorel delta is 3 300 000 t/a. Tributaries on the south shore of Lake St. Pierre, (mainly the Richelieu, Yamaska, St. Francis and Nicolet rivers) add another 1 330 000 t/a and tributaries on the north shore contribute 160 000 t/a. Solid input to the St. Lawrence River at the Lake St. Pierre outlet is thus about 4 800 000 t/a (Hydrotech, 1989).

On the north shore, then, it is the Ottawa River that contributes the most solid input, (and the solids are contaminated because of the industrial plants and population along the banks of the Ottawa River). Rivière L'Assomption comes next.

Four tributaries on the south shore empty very large solid loads (comparable to that of the Ottawa River) into Lake St. Pierre: the Richelieu, Yamaska, St. Francis and Nicolet rivers. Despite this input, Lake St. Pierre is not a major sink because most of the solid input leaves the lake: the lake is shallow and hydrodynamic conditions, ice effects and violent winds all promote transportation or resuspension of fine particles in the lake. The only areas conducive to long-term accumulation are sheltered spots such as the channels between the Sorel Islands (Hydrotech, 1989).

4.3.2 Sources of contamination

Industrial discharges. The following information on toxic input comes from Asseau (1992b and 1992c). There are 21 targeted plants in the subsystem. Locweld Inc. operates a surface treatment plant in Candiac that cleans and galvanizes steel for

5. These estimates are based on data collected in summer and fall; 60 to 70 percent of the solid load, however, passes through the St. Lawrence River in the spring (Hydrotech, 1989).

manufacture of steel towers. This plant discharges wastewater (0.00078 m^3/s) to the Candiac municipal sewer.

Perkins Papers Ltd. operates a plant in Candiac that manufactures toilet paper, paper napkins and paper tablecloths from recycled paper. The plant's only outfall discharges process water directly to the municipal system at a rate of 0.0545 m^3/s.

Monsanto Canada Inc. operates a tertiary organic chemicals plant in LaSalle that manufactures a variety of products, including maleic anhydride, polymers, resins and herbicides. Wastewater is discharged to the St. Lawrence River via three outfalls that empty into the St. Patrick collector. One of the outfalls discharges process water at an average rate of 0.0211 m^3/s. Since only this outfall has ever been characterized, the characterization of waste from this plant is incomplete as it does not cover all plant processes.

Héroux operates a surface treatment plant in Longueuil. The plant has a single outfall that discharges a mixture of process water, sanitary sewage and cooling water to the municipal sewer system. No quality data are available for this plant. Average discharge is 0.0057 m^3/s.

Pratt & Whitney builds airplanes in Longueuil. Metal parts for the engines require surface treatment. Wastewater from the plant's two outfalls has been characterized: one outfall collects sanitary sewage and process water and discharges to the municipal system; the other collects rainwater and empties into the river via a private sewer. Average combined discharge of the two outfalls is 0.0342 m^3/s.

Nacan Products Ltd. operates a tertiary organic chemicals plant in Boucherville that manufactures polyvinyl emulsions (adhesives) and resins by polymerization. The plant has three outfalls discharging a total 0.0186 m^3/s. One outfall discharges a small quantity of process water to the municipal sewer system; this is the only outfall that has ever been characterized.

Shell Canada Inc. operates a refinery in Montréal East that converts crude oil to gasoline, oil, bitumen and other products. The refinery has one private outfall that discharges rainwater and process water directly to the St. Lawrence River at an average rate of 0.148 m^3/s.

Noranda Copper Smelters and Refining (CCR Refinery) operates a refinery in Montréal East. The refinery has three combined sewers, all connected to the municipal system via the Durocher collector; total discharge of the three sewers is 0.329 m^3/s.

Union Carbide Canada Ltd. operates a secondary organic chemicals plant in Montréal East that converts refinery gas to a variety of products, among them polyethylenes, ethylene glycol, antifreezes and amines. The plant has three outfalls. Only one of the outfalls has been characterized, however, because it is the only one that collects process water (though it also collects cooling water and rainwater). This outfall discharges to the St. Lawrence River (0.0551 m3/s).

Kemtec Petrochemical Inc. operates a plant that manufactures a variety of products from naphtha and propane: fuel base, paraxylene, phenol, acetone and acetone derivatives. The plant closed down in 1991, but it used to have five outfalls connected to the Montréal East system. Only one of the five outfalls discharged process water, though it carried rain water as well. This was the only outfall characterized. Average discharge was 0.159 m^3/s.

Petro-Canada Products operates a petrochemical plant in Pointe aux Trembles that converts crude oil to light and heavy fuel oil, gasoline and asphalt. The plant has two outfalls, one that discharges process water to the St. Lawrence River and a second that collects sanitary sewage and is connected to the municipal sewage system. The outfall that carries process water has been characterized (average discharge is 0.214 m^3/s).

Commercial Alcohols Ltd. operated a secondary organic chemicals plant in Varennes that converted gaseous ethylene to ethyl alcohol and anhydrous ethyl alcohol before it shut down in 1991. All process water, sanitary sewage, rainwater and cooling water was discharged to the St. Lawrence River (0.0102 m^3/s) via the Pétromont outfall.

Albright & Wilson Amerique operated an organic chemicals plant in Varennes that produced elementary phosphorous and silicates from ore, coke and silica until it shut down in 1992. Combined discharge of the two outfalls from this plant was 0.0787 m^3/s. One outfall collected process water, sanitary sewage and cooling water and dumped it directly into the St. Lawrence River. The other outfall discharged rainwater to the St. Lawrence River via the Pétromont outfall.

Pétromont Inc. operates a secondary organic chemicals plant in Varennes that converts a variety of petroleum products (butane, ethane, propane and so forth) to ethylene, propylene, diverse oils and other products. The plant has a single outfall that discharges to the St. Lawrence River. This outfall collects effluent from a detention basin that contains only rainwater and from a settling pond that receives process water as well as rainwater. Only effluent from the settling pond (average discharge is 0.025 m^3/s) was characterized.

Hoechst Canada Inc. operates an inorganic chemicals plant in Varennes that produces polyvinyl acetate polymers from vinyl acetates. The plant has a single outfall that collects process water, rainwater, cooling water and sanitary sewage and dumps it directly into the St. Lawrence River (average discharge is 0.023 m^3/s). Characterization data available are not however representative of effluent quality.

Kronos Canada Inc. operates an inorganic chemicals plant in Varennes that manufactures titanium dioxide pigments from titanium slags, ilmenite ore and sulphuric acid. The plant has one outfall that discharges an average 0.570 m^3/s of process water, rainwater and cooling water directly to the St. Lawrence River.

Sidbec Dosco Ltd. operates a metallurgy plant in Contrecoeur that manufactures cold-rolled and hot-rolled steel, steel rods, reinforcing steel and primary billet and slab steel from iron ore, metallized pellets, scrap iron and lime. The plant has two outfalls that together discharge 0.594 m^3/s of rainwater, process water and cooling water directly to the St. Lawrence River. One of the outfalls also discharges sanitary sewage.

Wood Preservation Industries Ltd. operates a tertiary organic chemicals plant in Tracy which treats lumber, docks and poles with a variety of preservatives: creosote, pentachlorophenol and CGA. Since 1989, water generated by the plant has been recycled; before that, it was discharged to the Richelieu River. The plant has a sanitary sewer that is connected to the Tracy municipal sewage system.

Tioxide Canada Inc. operates an inorganic chemicals plant in Tracy that manufactures titanium dioxide pigments from titanium slags and/or ilmenite ore. The plant has two outfalls: a main outfall that discharges mainly process water to the St. Lawrence River (mean annual discharge is 0.154 m^3/s) and a combined sewer (rainwater and sanitary sewage) connected to the Tracy municipal system. Characterization data are for the main outfall.

QIT - Fer et Titane Inc. operates a metallurgy plant in Sorel that converts ilmenite and hard coal to titanium slags, cast iron, pig iron and steel billets. The plant has three outfalls (two for process water and one for rainwater) that empty into the St. Lawrence River and one sanitary sewer connected to the Tracy municipal sewage system. Discharge of the main outfall is about 1.8 m^3/s.

Atlas Steel (Sammi Atlas Inc. division) operates a metallurgy plant in Tracy that treats scrap iron and iron alloys and converts them to stainless steel foil and cable. The plant has two outfalls: an outfall that discharges 0.313 m^3/s of process water, cooling water, laboratory water and rainwater to the St. Lawrence River and a sanitary sewer that empties into the Tracy municipal system. Characterization data shown in Table 24 are valid except for the chromium values; chromium content has increased by 10 to 15 percent since the characterization.

Of the industrial plants that discharge wastewater to the St. Lawrence River between Montréal and Pointe du Lac, QIT - Fer et Titane contributes the most toxic input. This plant contributes more copper, chromium, mercury, cadmium, lead, zinc and nickel than any other plant in the subsystem. In fact, the plant contributes more to deterioration of the environment, because of the quantity and quality of its discharges, than any other

Table 24 ***Measured industrial metal (Cu, Zn, Pb, Ni, Cd, Cr and Hg) input between the La Prairie Basin and Pointe du Lac (Asseau, 1992b and 1992c)***

Plant	Cu (kg/d)	Zn (kg/d)	Pb (kg/d)	Ni (kg/d)	Cd (kg/d)	Cr (kg/d)	Hg (kg/d)
Monsanto							
Locweld	0.022	0.34		0.020	<0.0021	0.026	
Perkins Papers	0.10						<0.001
Noranda	4.1	2.0	0.44	0.27	0.02	0.20	
Shell Canada	<0.28	1.1	<0.46	0.56	<0.28	<0.46	<0.002
Union Carbide		0.87				1.3	
Kemtec			1.8			<3.2	
Petro Canada	0.94	4.9	1.9	<0.94	<0.47	1.8	<0.0038
Pratt & Whitney Canada	0.085	0.19	<0.15	<0.15		<0.023	
Nacan Products		0.019					
Commercial Alcohols		0.19		11		0.063	0.0004
Albright & Wilson	0.12	14	0.22	0.12	0.013	<0.044	0.0074
Kronos Canada	3.5	9.4	6.9	9.4	0.56	187	0.11
Pétromont		0.54				0.35	
Sidbec Dosco	0.51	7.0	<5.1	1.1	<0.35	<0.16	
Sammi Atlas	0.99	0.42		9.1	<1.5	116*	0.0046
Tioxide Canada	<0.48	4.2	<13.3	2.28	0.26	193	0.011
QIT - Fer et Titane	401	380	43	224	0.21	325	0.14

Base year: 1989
Inaccuracy of industrial input: about 30%
* Increase of 10 to 15% not incorporated

plant between Cornwall and Pointe du Lac. Tioxide Canada Inc. and Kronos Canada Inc. also contribute large amounts of chromium. In addition, the effluent from Kronos Canada Inc. contains mercury. The effluent from Tioxide Canada Inc. is extremely acid (pH 1.1); this affects organisms in the environment directly and indirectly because acidity promotes solubilization of metals. Atlas Inc. also contributes a lot of chromium.

Tributaries. Asseau (1992b and 1992c) conducted a survey of toxic input from subsystem tributaries. Table 25 shows survey results for metals measured in all subsystem tributaries.

Rivière des Prairies and the Richelieu River top the list for toxic input from subsystem tributaries, contributing 36 and 35 percent of total tributary input to the subsystem respectively. Discharge of Rivière des Prairies is almost three times that of the Richelieu River, yet toxic loads of the two rivers are comparable. Next comes the St. Francis River; it contributes 9.8 percent of total tributary input. Rivière L'Assomption contributes 3.1 percent and all other streams together contribute less than 1 percent of total toxic input.

Two tributaries dominate for all metals: Rivière des Prairies (zinc, nickel and cadmium) and the Richelieu River (copper, zinc, lead, nickel and cadmium). The St. Francis River is loaded mainly with zinc, lead, copper and nickel, but not as heavily as Rivière Des Prairies and the Richelieu Rivers. The other tributaries contribute little to subsystem toxic load. Spring load is significantly higher than summer load in all streams.

Copper comes to subsystem 2b mainly from the Richelieu River (69 percent of input). In fact, the Richelieu River ranks second among the tributaries of the St. Lawrence River for copper input, after the St. Maurice River. Rivière des Prairies and the St. Francis River contribute 17 and 6 percent respectively of total copper input to the subsystem and rank third and fourth for copper input among tributaries of the St. Lawrence River.

Table 25 Tributary metal input (Cu, Zn, Pb, Ni and Cd) between the La Prairie basin and Pointe du Lac (Asseau, 1992b and 1992c)

Tributary	Cu (kg/d)	Zn (kg/d)	Pb (kg/d)	Ni (kg/d)	Cd (kg/d)
St. Jacques River	0.8	3.0	0.8	0.9	0.06
Rivière de la Tortue	0.6	29	0.6	0.7	--
St. Régis River	--	--	0.3	--	--
Rivière des Mille Îles	39	515	15	21	9.4
Rivière des Prairies	390	2 361	90	115	55
Rivière L'Assomption	50	144	49	--	--
St. Francis River	149*	407*	216*	96	19
Yamaska River	84	378	71	47	9.5
Richelieu River	1 621	840	265	177	35
Bayonne River	3.2*	6.8*	8.5*	--	0.4
Maskinonge River	5.9	7.4	10.7	--	1.3
Rivière du Loup	13	14	25	--	2.0
TOTAL	2 356.5	4 705.2	751.9	-	-

Base years: 1985-1986-1988
Input inaccuracy: 25 to 35%
-- No data available
* Includes municipal input to certain Lake St. Pierre tributaries and downstream of gauging stations

Zinc comes mainly from Rivière des Prairies; this river contributes more zinc than any other St. Lawrence River tributary. Rivière des Mille Îles and the Richelieu, St. Francis and Yamaska rivers also contribute substantial zinc input, respectively, 11, 18, 9 and 8 percent of total zinc input to the subsystem.

Lead comes mainly from the Richelieu and St. Francis rivers; these rivers contribute 35 and 29 percent of total lead input from subsystem tributaries. Although other tributaries downstream contribute more lead (the Ste. Anne, St. Maurice and Nicolet rivers), the contribution of the Richelieu and St. Francis rivers is significant.

Municipalities. Table 26 shows municipal discharges to subsystem 2b. Every day in 1989, the St. Lawrence River received some 70 kg of copper, 260 kg of zinc and 120 kg of lead from municipal discharges to subsystem 2b. These are the highest municipal toxic loads discharged to the St. Lawrence River corridor. Three-quarters of the copper, zinc and lead input came from Montréal Island municipalities. There is nothing surprising about this since the island is the most densely populated area of Québec (1.75 million inhabitants). Other Montréal area urban communities on the south shore (but including Repentigny) contributed 20 percent of toxic input of the three reference metals to the subsystem.

In 1989, the La Prairie basin received wastewater from 17 municipalities. Nine of these municipalities are on the territory of the Montréal Urban Community (MUC) but were not yet connected to the MUC's wastewater treatment plant. The other eight municipalities are on the south shore. Population of the 17 municipalities is 438 000 inhabitants. These municipalities contributed a total daily input of 12.2 kg of copper, 46.0 kg of zinc and 22.6 kg of lead.

The Verchères-Contrecoeur region received wastewater from 10 municipalities with a total population of 69 000 inhabitants.

The municipalities of Sorel and Tracy at the Lake St. Pierre inlet contribute close to 2 percent of total municipal discharges to subsystem 2b. Total population of the municipalities is 42 300. Input from these municipalities is relatively insignificant; its effect on the quality of life of aquatic organisms in Lake St. Pierre is discussed in section 4.3.3 below. Other subsystem municipalities contribute little to toxic loads in the St. Lawrence River.

As in subsystems upstream, zinc was more abundant than the other two reference metals in municipal effluents: zinc load was double lead load and triple copper load.

Table 26 Municipal metal (Cu, Zn and Pb) input in 1989 between the La Prairie basin and Pointe du Lac (Asseau, 1992b and 1992c)

Municipality	Cu (kg/d)	Zn (kg/d)	Pb (kg/d)
Lasalle	2.4	9.7	4.7
Verdun	1.9	7.7	3.8
Lachine	1.1	4.5	2.2
Côte St. Luc	0.90	3.7	1.8
Outremont	0.38	0.96	0.48
Westmount	0.33	0.83	0.42
Hampstead	0.12	0.31	0.15
Montreal West	0.089	0.22	0.11
St. Pierre	0.082	0.21	0.10
St. Hubert	1.9	7.6	3.7
Brossard	1.8	7.3	3.6
St. Lambert	0.34	0.85	0.43
Greenfield Park	0.31	0.77	0.39
Candiac	0.17	0.41	0.21
La Prairie	0.17	0.41	0.21
Lemoyne	0.12	0.30	0.15
Ste. Catherine	0.12	0.29	0.15
MUC (treatment plant)*	23.9	72.3	30.9
Montréal	22.1	89.7	43.7
Longueuil	8.0	32.5	15.9
Boucherville	0.96	3.9	1.9
Montréal East	0.060	0.15	0.075
Repentigny	1.2	4.7	2.3
Lachenaie	0.16	0.39	0.20
Varennes	0.068	0.17	0.085
Contrecoeur	0.037	0.093	0.047
Verchères	0.051	0.13	0.064
Lavaltrie	0.033	0.083	0.041
Lanoraie	0.024	0.060	0.030
St. Joseph de Lanoraie	0.022	0.054	0.027
St. Sulpice	0.017	0.041	0.021
St. Antoine de Lavaltrie	0.012	0.029	0.015
Sorel and Tracy	1.69	6.86	3.34
Berthierville	0.06	0.49	0.078
Pointe du Lac	0.05	0.22	0.11
St. Ignace de Loyola	0.03	0.13	0.06
TOTAL	70.71	258.06	121.49

Base year: 1989
Inaccuracy of municipal input: 50%
* The MUC treatment plant served 18 municipalities in 1989.

Upstream St. Lawrence River reaches. Discharge from upstream reaches of the St. Lawrence River constitutes 80 percent of total flow in the Montréal area and 90 percent of total flow in Lake St. Pierre. Toxic input at the Lake St. Louis outlet has been estimated at 317 058 kg/a of copper, 1 287 836 kg/a of zinc and 158 091 kg/a of lead. These values reflect total input from industrial plants, tributaries and municipalities discharging waste to Lake St. Louis together with toxic input from upstream reaches of the St. Lawrence River estimated at the Lake St. Louis entrance.

This theoretical estimate has not been checked against gauging station data. It is based on the assumption that all loads discharged to the river are transported downstream. Load estimates based on water quality data collected in 1986 at gauging stations in Lanoraie give some idea of the validity of the theoretical estimate. According to this data, at Lanoraie the St. Lawrence River inputs 742 738 kg/a of copper, 1 078 022 kg/a of zinc and 216 207 kg/a of lead. This suggests a very large quantity of zinc (1 400 000 kg/a) and a smaller amount of lead (26 000 kg/a) is deposited on the way to Lake St. Pierre. The reverse was true for copper. The gauging station data suggest the theoretical estimate was short by 220 000 kg/a, indicating that input from known sources has been underestimated or that there are other sources of copper that have not been accounted for.

Summary. Table 27 shows all toxic input to subsystem 2b. The subsystem receives more toxic input of the three reference metals than any other stretch of the St. Lawrence River. Tributaries make the largest contribution. Rivière des Prairies provides the most toxic input of the subsystem's tributaries, followed by the Richelieu River, the St. Francis River, Rivière des Mille Îles and the Yamaska Rivers, in that order. These rivers contribute five times more copper, zinc and lead than the tributaries of Lake St. Louis and several hundred times more of these metals than the tributaries of Lake St. Francis. Zinc is the most abundant contaminant, quantitatively (1 717 411 kg/a), followed by copper (860 373 kg/a) and lead (274 469 kg/a).

Table 27 ***Annual metal (Cu, Zn and Pb) input from the four main sources of contamination between the La Prairie basin and Pointe du Lac (Asseau, 1992b and 1992c)***

Source	Cu (kg/a)	Zn (kg/a)	Pb (kg/a)	%
Industrial plants				
Upstream of Lanoraie	3 440	14 724	3 102	6.1
Lanoraie - Pointe du Lac*	147 051	140 623	18 129	
Tributaries				
Upstream of Lanoraie	175 346	1 113 980	56 831	53.0
Lanoraie - Pointe du Lac*	685 027**	603 431**	217 638**	
Municipalities				
Upstream of Lanoraie	26 105	91 428	43 000	3.1
Lanoraie - Pointe du Lac*	690	2 811	1 369	
Upstream St. Lawrence River reaches				
Lake St. Louis outlet	317 058	1 287 836	158 091	37.8
Lanoraie gauging station*	742 738	1 078 022	216 207	
TOTAL INPUT	1 575 506	1 824 887	453 343	100

Inaccuracy of industrial input: 30%
Inaccuracy of tributary input: 25 to 45%
Inaccuracy of municipal input: 30 to 50%
Inaccuracy of upstream St. Lawrence River reaches input: 45 to 85%
* This input was used to compute total input to the subsystem.
** Input of municipalities downstream of the gauging station is included.

Upstream reaches of the St. Lawrence River rank second as a source of contaminants, contributing 40 percent of toxic input. These waters contribute mainly to zinc, copper and lead contamination (in descending order). Concentrations of the three reference metals at Lanoraie were compared with total input of each metal to Lake St. Louis; the comparison indicated that some of the zinc and lead is deposited in Lake St. Louis, the lesser La Prairie basin or the Montréal-Lanoraie stretch and that there is copper input that has not been accounted for.

Though an impressive number of industrial plants were studied (18) and though industrial toxic input to subsystem 2b is much greater than industrial input to subsystems upstream (45 times input to Lake St. Louis), industrial discharges still rank third for toxic input to the subsystem, contributing only 6 percent of total contaminant load. Zinc and copper input is about seven times lead input. The zinc and copper come mainly from the Sorel-Tracy area.

Though municipal input to subsystem 2b far exceeds municipal input anywhere else along the St. Lawrence River corridor (the subsystem serves 35 municipalities with 2.3 million people), it is still small compared to other sources of contamination (upstream reaches of the St. Lawrence River and tributaries).

4.3.3 **Particle-size distribution.** Figures 38 and 39 and Table 28 show dominant size fractions in areas of subsystem 2b for which data were available.

Substratum of the Lachine rapids and the greater La Prairie basin is dominated by rock and gravel. Strong currents prevent deposition of fine material. Fine material does however settle in the weedbeds of the greater La Prairie basin and downstream of the Verdun jetties, where slower currents promote sedimentation.

Substratum of the lesser La Prairie basin however is a thick relatively uniform layer of fine sediment accumulated since the seaway dike was built some thirty years ago. Water level regulation at both ends of the basin together with the slow currents promote sedimentation of fine particles. Dominant size fractions in this basin, in descending order, are clay, silt and sand. Much of the sediment comes from the Châteauguay River, whose waters run down the right shore of Lake St. Louis as soon as they enter the lake.

The bottom has not been sampled much between the rapids under Victoria bridge and Lanoraie; data that are available however indicate it is composed of gravel, rock or compact marine clay. In the main channel, strong currents (> 0.6 m/s) prevent sedimentation. Montréal harbour, however, and the many archipelagos in the southern part of the subsystem are conducive to deposition. Characteristic of this stretch is a difference in particle sizes on the north and south sides; material is much coarser on the north side than on the south side. As expected then, areas favourable for accumulation of sediment are on the south side: the two main sedimentation areas are the Longueuil-

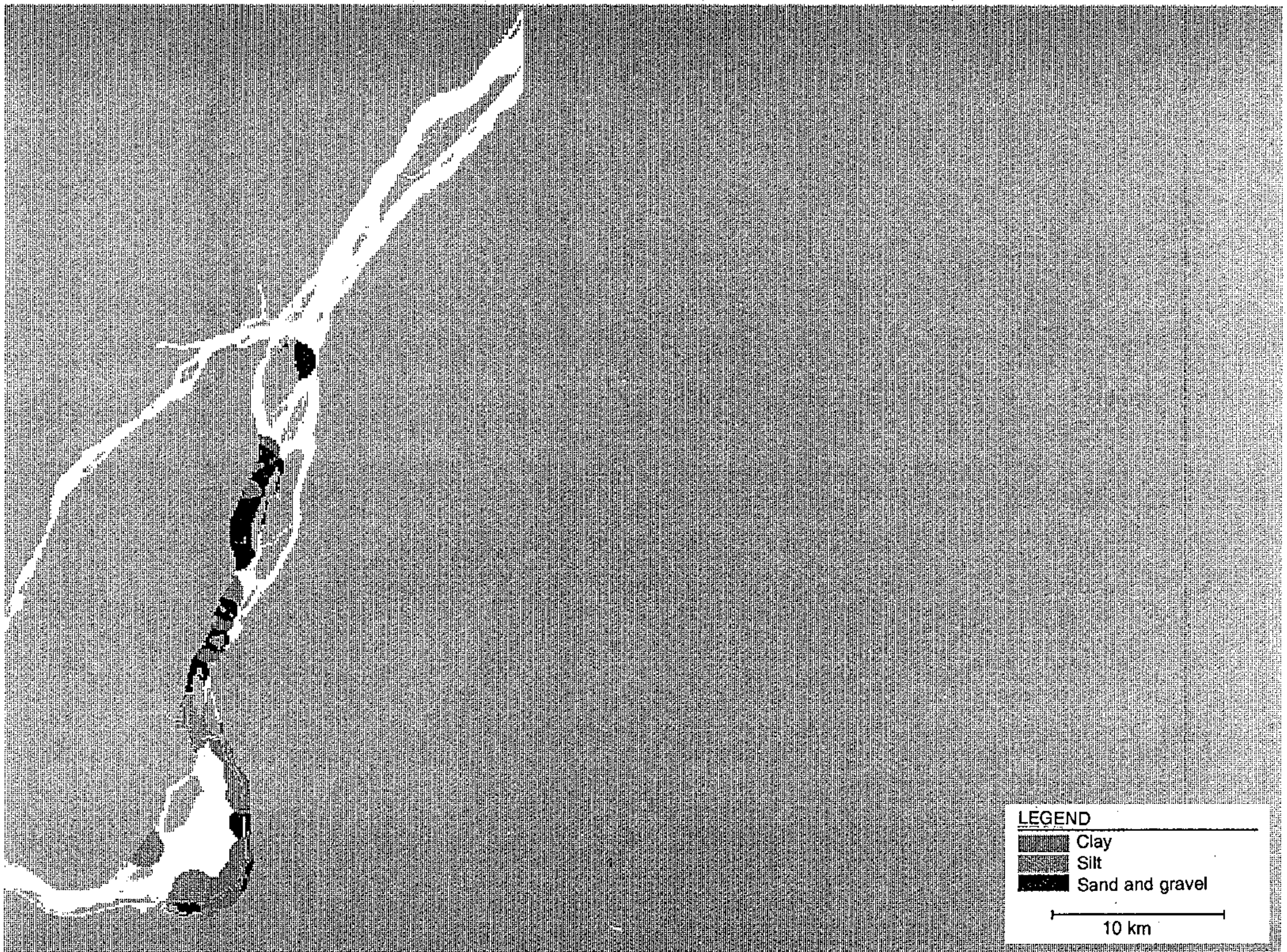


Figure 38 ***Dominant size fractions between La Prairie and Lavaltrie***

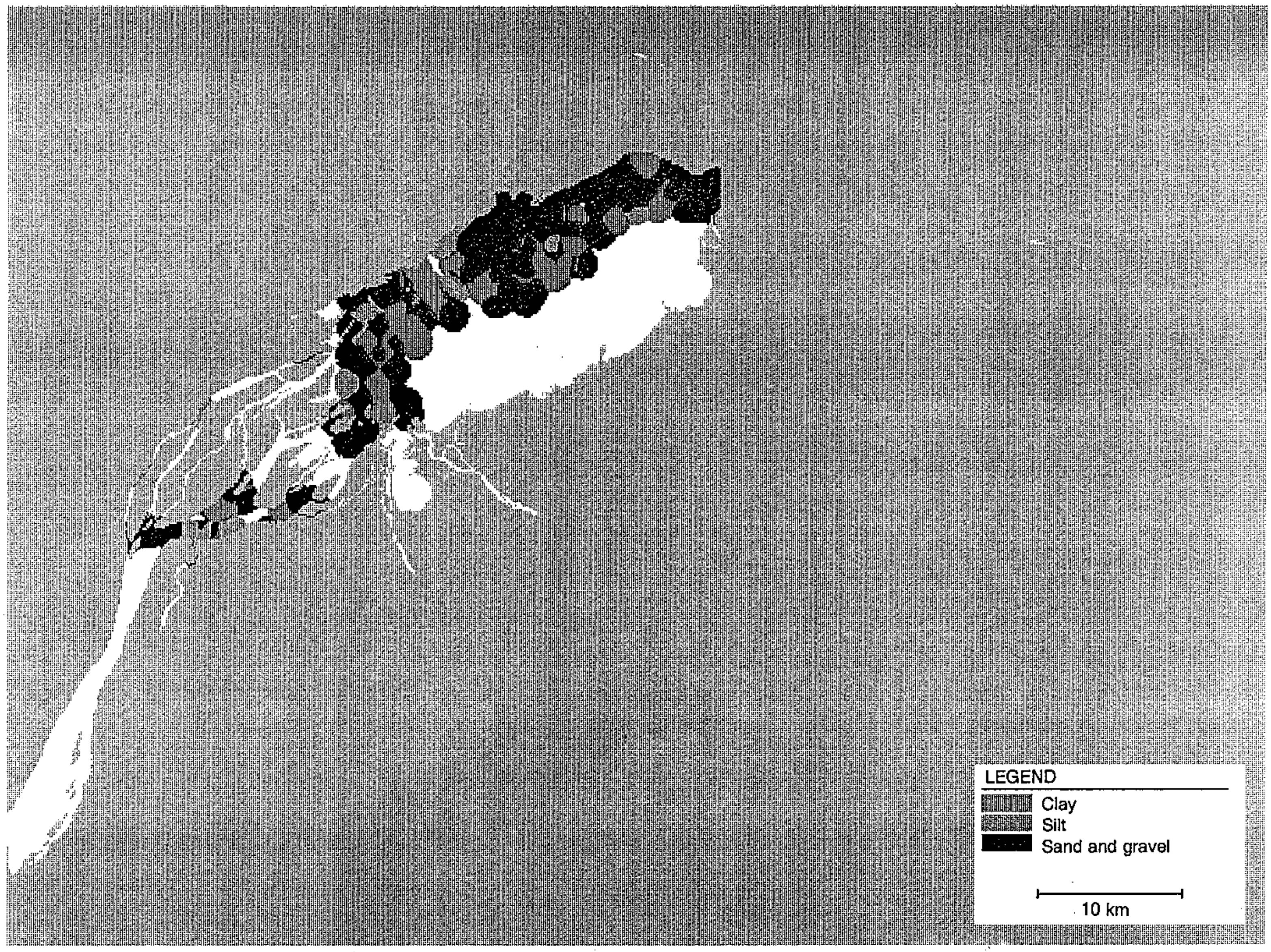


Figure 39 Dominant size fractions between Lavaltrie and Pointe du Lac

Table 28 Dominant size fractions in subsystem 2b

Area	Size class	Number of stations	Mean %	Standard deviation	Minimum %	Maximum %
Lesser La Prairie basin	Clay	29	41	17	0	79
	Silt	29	39	17	0	73
	Sand	29	20	22	2	100
Montréal-Sorel corridor	Clay	60	25	18	3	100
	Silt	60	29	18	0	87
	Sand	60	46	22	0	93
Sorel delta	Clay	23	28	13	0	47
	Silt	23	35	17	0	73
	Sand	23	37	27	5	100
Lake St. Pierre	Clay	134	21	18	0	75
	Silt	134	20	16	0	72
	Sand	134	59	30	1	100

Boucherville shoreline and the Contrecoeur Islands. Average rate of sedimentation around the Contrecoeur Islands is 0.5 cm/a (Couillard, 1987).

The islands on the edge of the shipping channel are eroding at a rapid rate, mainly due to lapping from the wake of commercial ships, ice action and wind-generated waves. The Sydor model (1978) suggests some of the eroded material will settle in the shelter of the islands and the rest will continue down to Lake St. Pierre.

According to Hydrotech (1989), the bottom is much sandier on the north side between Varennes and Sorel, especially in the secondary shipping channel, but currents do transport sediment at certain times of the year. Hydrotech (1989) also states that between Lanoraie and Sorel the bottom is mainly of sand and gravel and that the substratum becomes coarser with depth. At the Sorel Islands, the bottom of the shipping channel is entirely of marine clay; this area, where currents exceed 1 m/s, is definitely not favourable for sedimentation. Strong currents coupled with lapping cause major erosion of islands bordering the channel.

The Sorel delta, on the other hand, is a vast deposition site for sand and fine sediment. The submerged sills built in the secondary channels to raise water level upstream slow down currents in the channels, turning some of them into immense sedimentation basins. Sedimentation rate is sometimes as high as 1 cm/a, especially in areas under the influence of the submerged sills (Couillard, 1987). However, given the complex hydrodynamics of the channels, intensified by seasonal effects of vast submerged weedbeds, substratum particle size is not uniform. Dominant size fraction is sand (37 percent), although silt and clay are almost as abundant (35 and 28 percent respectively). Sediment particle size is more homogeneous in this area than elsewhere in the lake, however (Hardy et al., 1991b). Specifically, sand occurs mainly upstream and downstream of the islands and coarse silt is found in the channels and downstream of the islands.

In Lake St. Pierre, sand is more dominant (59 percent). Silt and clay (that is, fine particles) constitute 20 and 21 percent respectively of lake sediment. This may not, however, be an accurate picture of particle-size distribution in the southern part of the lake: the southern part of the lake belongs to the Department of National Defence and could not be sampled for security reasons. The mouth of Rivière du Loup differs from the rest of the lake; the percentage of fine material is higher here. Sedimentation is possible downstream of the Sorel delta because of the protection the islands offer.

Bottom material gets coarser and coarser towards the lake outlet, where it is only sand and gravel. Particle size tends to increase downstream, corroborating the conclusion drawn by Centreau (1974), Caillé et al. (1974), Cluis et al. (1975) and Couillard (1987) that Lake St. Pierre is not favourable for deposition of fine sediment. The particle-size distribution map of the lake and the observations of Hydrotech (1989) suggest however that a fine sediment fraction is deposited seasonally during the period of low runoff and then transported downstream during flooding or high winds.

About 19 500 m^3 of sediment (mainly sand) are dredged from the shipping channel every year; currents slow down enough in bends of the shipping channel and around anchorages to promote sedimentation of coarse sand.

For a complete picture of sediment quality in subsystem 2b, a survey of particle-size distribution between Montréal and Sorel and in the southern part of Lake St. Pierre is required.

4.3.4 Physical chemistry. Only partial data are available on sediment quality in subsystem 2b. Mercury data collected in 1976 in the lesser La Prairie basin showed moderate contamination (median of 0.46 µg/g) of the entire basin. Highest concentrations (2.77 µg/g) (Table 29) were mainly detected close to the Candiac municipal outfall (Figure 40).

Table 29 Lesser La Prairie basin sediment quality statistics

Year	Metal	Number of samples	% samples below detection level	Mean (µg/g)	Standard deviation (µg/g)	Median (µg/g)	Minimum (µg/g)	Maximum (µg/g)
1976*	Pb	17	0	81.06	91.91	48.00	18.00	400.00
	Cd	17	0	9.00	1.37	9.00	7.00	12.00
	Zn	17	0	571.71	745.55	315.00	127.00	3 090.00
	Hg	17	0	0.74	0.81	0.46	0.06	2.77
	Ni	17	0	47.36	8.38	48.40	32.80	65.00
	Cu	17	0	58.08	30.24	55.30	29.20	163.00
	Cr	17	0	72.15	10.93	73.00	51.20	88.70
1987**	Pb	18	0	144.78	49.81	137.00	71.00	295.00
	Cd	18	61	1.39	0.21	<1.00	<1.00	1.70
	Zn	18	0	455.72	208.31	392.00	120.00	922.00
	Hg	18	0	0.35	0.06	0.34	0.25	0.50
	Ni	18	0	39.72	6.39	41.10	24.10	46.80
	Cu	18	0	61.04	12.09	62.90	34.50	78.50
	Cr	18	0	105.14	21.86	105.00	64.30	153.00

* Sérodes (1978)
** Hardy et al. (1991b)

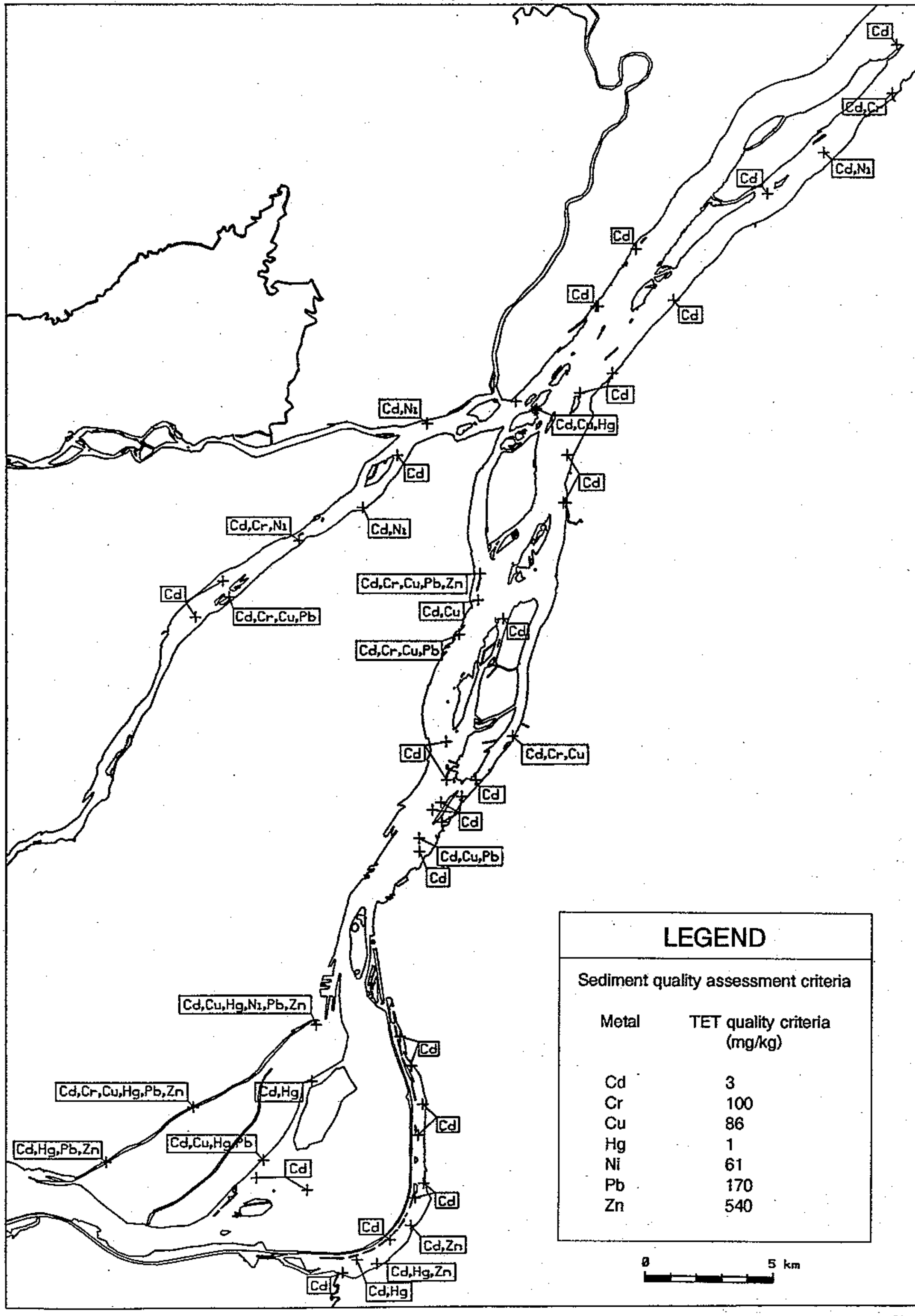


Figure 40 ***Exceedences of TET quality criteria between the La Prairie basin and Lavaltrie (1976)***

One known mercury source is the Candiac sewer, but the contamination may also be partly due to contaminated sediment transported from the area southeast of Îles de la Paix. The lesser La Prairie basin is vulnerable to contamination from upstream because of its geographic position and low hydraulic friction.

Moderate to high mercury concentrations were also detected near the old power plant in Verdun, in Montréal harbour, in the southern part of the Boucherville, St. Thérèse and Contrecoeur archipelagos, in the Sorel delta and at the Lake St. Pierre entrance (tables 30 to 33). In all cases, the contamination was localized (Figures 41 and 42). In general, mercury levels were low in 1976 between Montréal and Sorel (median of 0.01 µg/g) and in Lake St. Pierre (median 0.07 µg/g).

In 1976, copper was distributed quite uniformly throughout the lesser La Prairie basin, the Montréal-Sorel corridor and Lake St. Pierre; on the whole, contamination was moderate (medians were 55.3, 39.3 and 33 µg/g respectively). High concentrations of copper were detected at the old Verdun power plant, in Montréal harbour, south of the Boucherville archipelago and downstream of Ste. Thérèse Island (Figure 43). Median concentration of mercury was higher in the Sorel delta (35.9 µg/g) than in Lake St. Pierre or the Montréal-Sorel corridor but comparable to that of the lesser La Prairie basin. Highest copper concentrations were detected in Montréal harbour (2 550 µg/g), in the lesser La Prairie basin (163 µg/g), and south of the Sorel delta (close to the Sorel-Tracy industrial complex and the mouth of the Richelieu River) (121 µg/g); thereafter, copper levels decreased gradually downstream in the lake.

In 1976, zinc contamination decreased upstream to downstream in the subsystem. Though moderate, median zinc concentration was higher in the lesser La Prairie basin (315 µg/g) than in the Montréal-Sorel corridor (119 µg/g) or in Lake St. Pierre (114 µg/g). Zinc was distributed relatively uniformly throughout the lesser La Prairie basin--except downstream of the Candiac outfall, where one station recorded very high zinc levels (3 090 µg/g) (Figure 44).

Table 30 *Montréal-Sorel corridor sediment quality statistics*

Year	Metal	Number of samples	% samples below detection level	Mean (µg/g)	Standard deviation (µg/g)	Median (µg/g)	Minimum (µg/g)	Maximum (µg/g)
1976*	Pb	39	0	43.31	63.96	22.00	0.00	315.00
	Cd	39	0	6.92	2.38	7.00	1.00	13.00
	Zn	39	0	159.54	118.46	119.00	25.60	574.00
	Hg	39	0	0.22	0.24	0.12	0.01	1.06
	Ni	39	0	36.08	14.95	32.60	5.80	70.80
	Cu	39	0	137.54	417.04	39.30	5.90	2550.00
	Cr	39	0	68.61	26.24	61.60	22.90	142.00

* Sérodes (1978)

Table 31 *Lake St. Pierre (including the Sorel delta) sediment quality statistics*

Year	Metal	Number of samples	% samples below detection level	Mean (µg/g)	Standard deviation (µg/g)	Median (µg/g)	Minimum (µg/g)	Maximum (µg/g)
1976*	Pb	104	1	23.29	20.45	15.00	0.00	105.00
	Cd	105	0	6.24	2.14	6.00	0.00	11.00
	Zn	105	0	124.99	59.93	114.00	0.00	314.00
	Hg	104	3	0.17	0.33	0.07	0.01	2.34
	Ni	105	0	36.38	16.81	32.70	0.00	76.70
	Cu	105	0	39.05	23.53	33.00	0.00	121.00
	Cr	105	0	77.67	37.71	71.00	0.00	243.00
1986**	Pb	37	0	36.92	25.77	30.00	7.60	125.00
	Cd	36	94	1.51	0.52	<1.00	<1.00	1.87
	Zn	37	0	153.75	68.26	145.00	44.30	329.00
	Hg	37	3	0.16	0.12	0.12	0.01	0.50
	Ni	37	0	39.50	24.69	30.90	10.40	103.00
	Cu	37	0	50.78	34.35	42.20	3.01	123.00
	Cr	37	0	126.22	79.46	100.00	33.30	314.00

* Sérodes (1978)
** Hardy et al. (1991)

Table 32 ***Median metal concentrations in three areas of Lake St. Pierre (µg/g)***

Year	Metal	Sorel delta	Upstream	Centre
		Median	Median	Median
1976*	Pb	25.00	13.00	10.00
	Cd	6.00	6.00	6.00
	Zn	124.00	108.00	86.00
	Hg	0.10	0.04	0.03
	Ni	31.90	28.40	31.80
	Cu	35.90	35.80	25.00
	Cr	71.50	64.30	57.00
1986**	Pb	52.30	27.40	18.70
	Cd	<1.00	<1.00	<1.00
	Zn	234.00	136.00	121.00
	Hg	0.15	0.13	0.09
	Ni	51.80	30.90	28.60
	Cu	89.30	46.20	31.20
	Cr	155.00	91.30	91.70

* Sérodes (1978)
** Hardy et al. (1991)

Montréal harbour (in the Montréal-Sorel corridor) was highly contaminated by zinc (maximum was 574 µg/g). Zinc contamination was moderate at the old power plant in Verdun and in the Boucherville and Contrecoeur archipelagos.

The Sorel delta and most of Lake St. Pierre are slightly zinc-enriched. Moderate contamination was detected near the Sorel-Tracy industrial complex, at the mouth of the Richelieu River and in the southern part of Lake St. Pierre.

Lead distribution pattern, like that of zinc, showed a gradual decrease in median concentrations between Lachine and Pointe du Lac: medians in the lesser La Prairie basin, the Montréal-Sorel corridor and Lake St. Pierre were, respectively, 48 µg/g, 22 µg/g and 15 µg/g.

Table 33 ***Maximum metal concentrations in three areas of Lake St. Pierre (µg/g)***

Year	Metal	Sorel delta	Upstream	Centre
		MAXIMUM	MAXIMUM	MAXIMUM
1976*	Pb	105.00	52.00	36.00
	Cd	9.00	10.00	11.00
	Zn	314.00	223.00	258.00
	Hg	2.18	0.30	0.48
	Ni	54.50	62.00	76.20
	Cu	98.40	70.20	98.70
	Cr	101.00	172.00	172.00
1986**	Pb	74.80	47.20	48.80
	Cd	1.87	1.14	1.00
	Zn	329.00	304.00	229.00
	Hg	0.50	0.23	0.28
	Ni	103.00	54.60	41.20
	Cu	123.00	58.60	73.80
	Cr	308.00	137.00	122.00

* Sérodes (1978)
** Hardy et al. (1991)

Unlike the other metals, lead was not uniformly distributed in the lesser La Prairie basin; concentrations increased upstream to downstream, suggesting contamination stems mainly from local sources (Figure 45). Contamination was on the whole moderate, though levels as high as 400 µg/g were detected.

Though on the whole the Montréal-Sorel corridor is only slightly lead-contaminated, high concentrations of lead were detected at the old power plant in Verdun and in Montréal harbour (maximum of 315 µg/g). Moderate contamination was detected in the Boucherville and Contrecoeur archipelagos downstream of municipal and industrial outfalls.

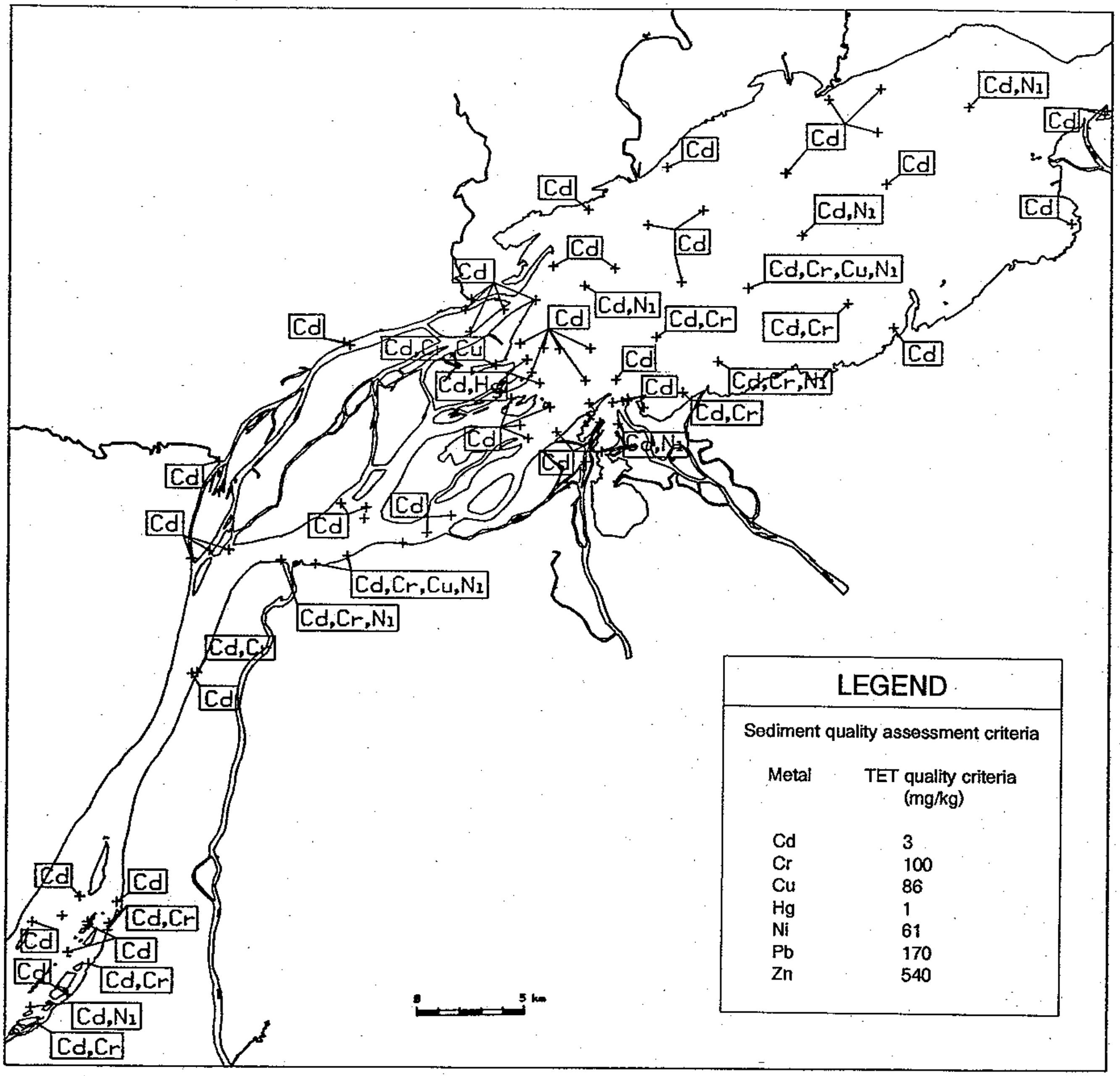


Figure 41 ***Exceedences of TET quality criteria between Lavaltrie and Pointe du Lac (1976)***

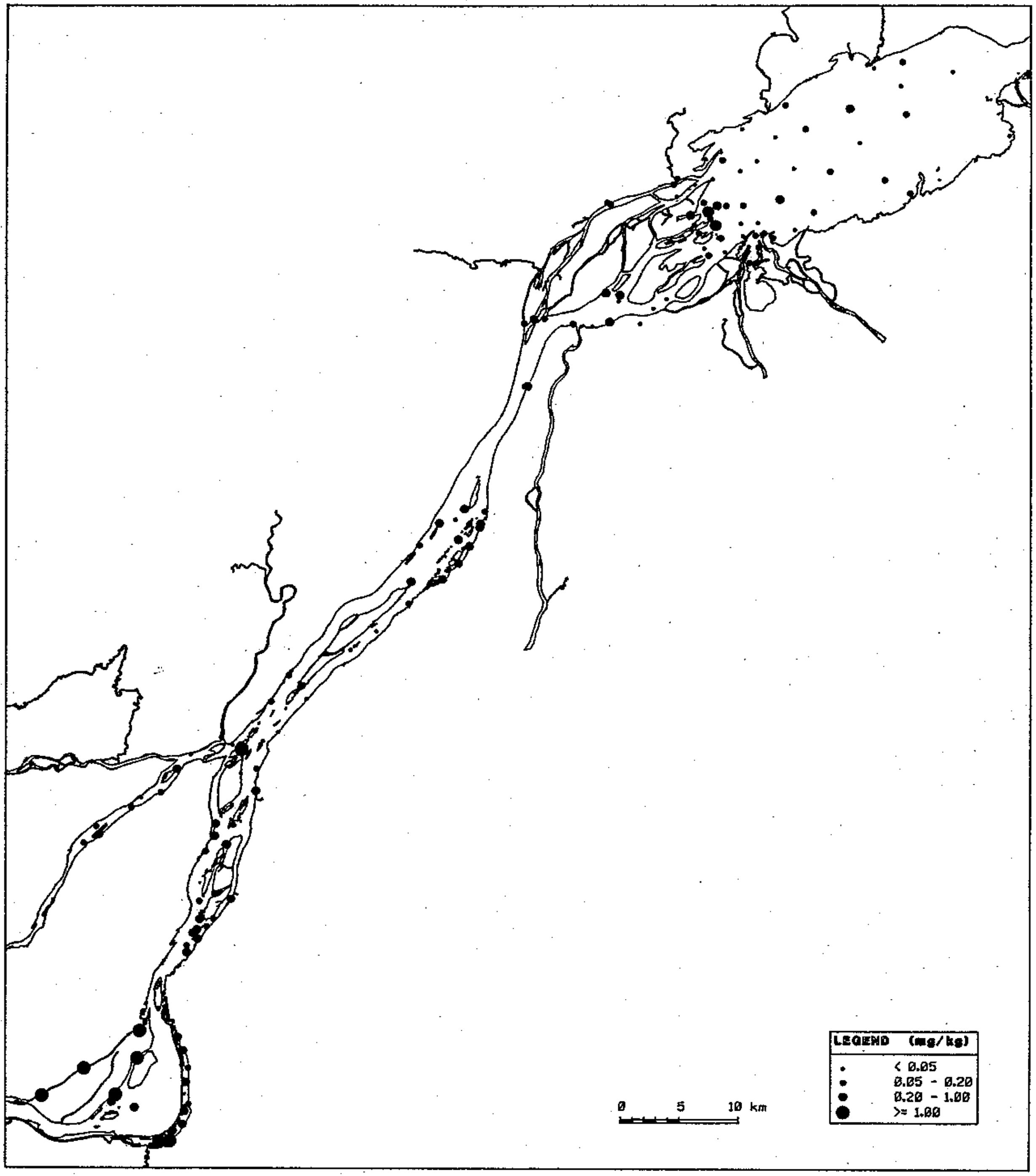


Figure 42 ***Mercury distribution in sediment between the La Prairie basin and Pointe du Lac (1976)***

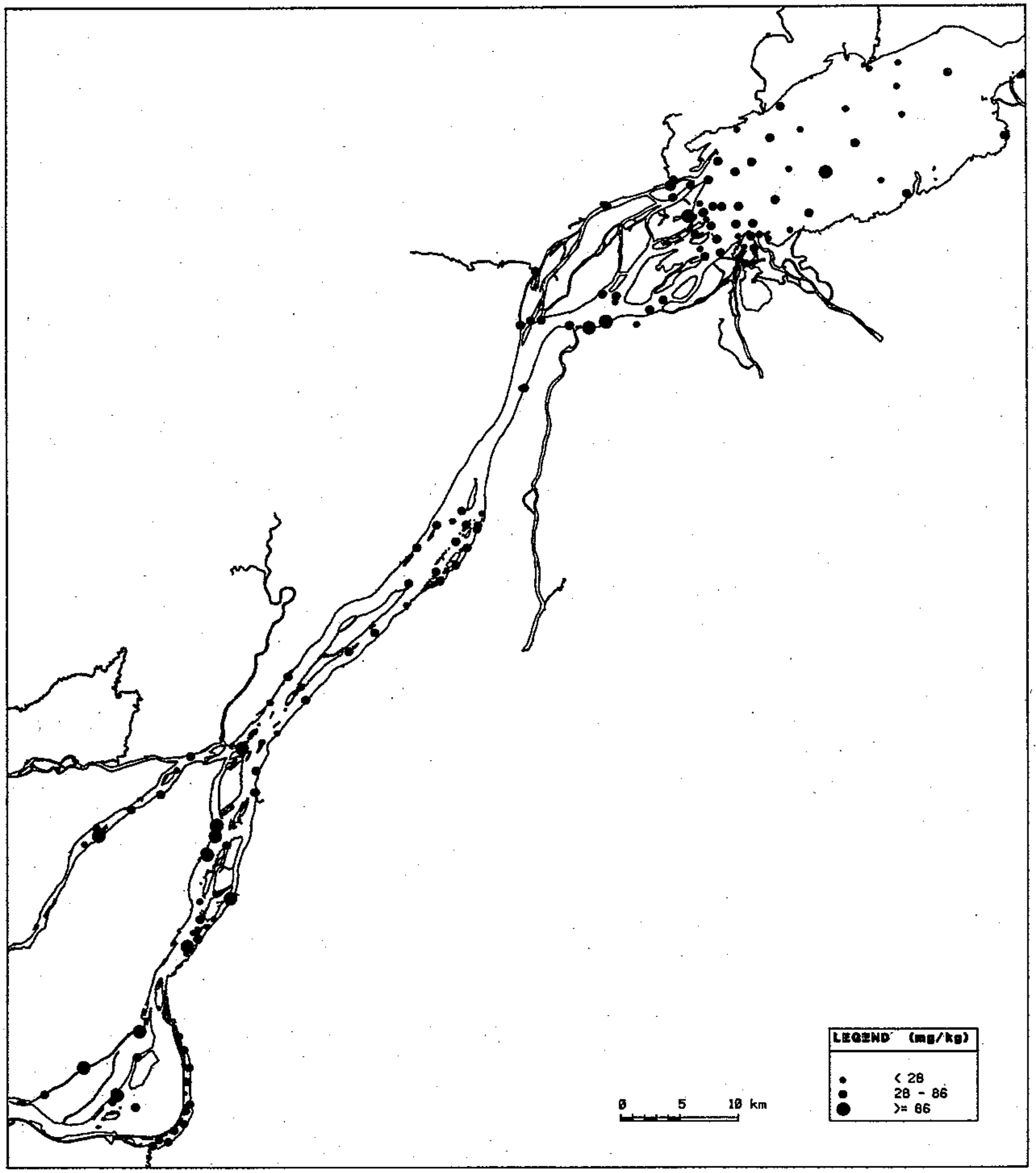


***Figure 43** Copper distribution in sediment between the La Prairie basin and Pointe du Lac (1976)*

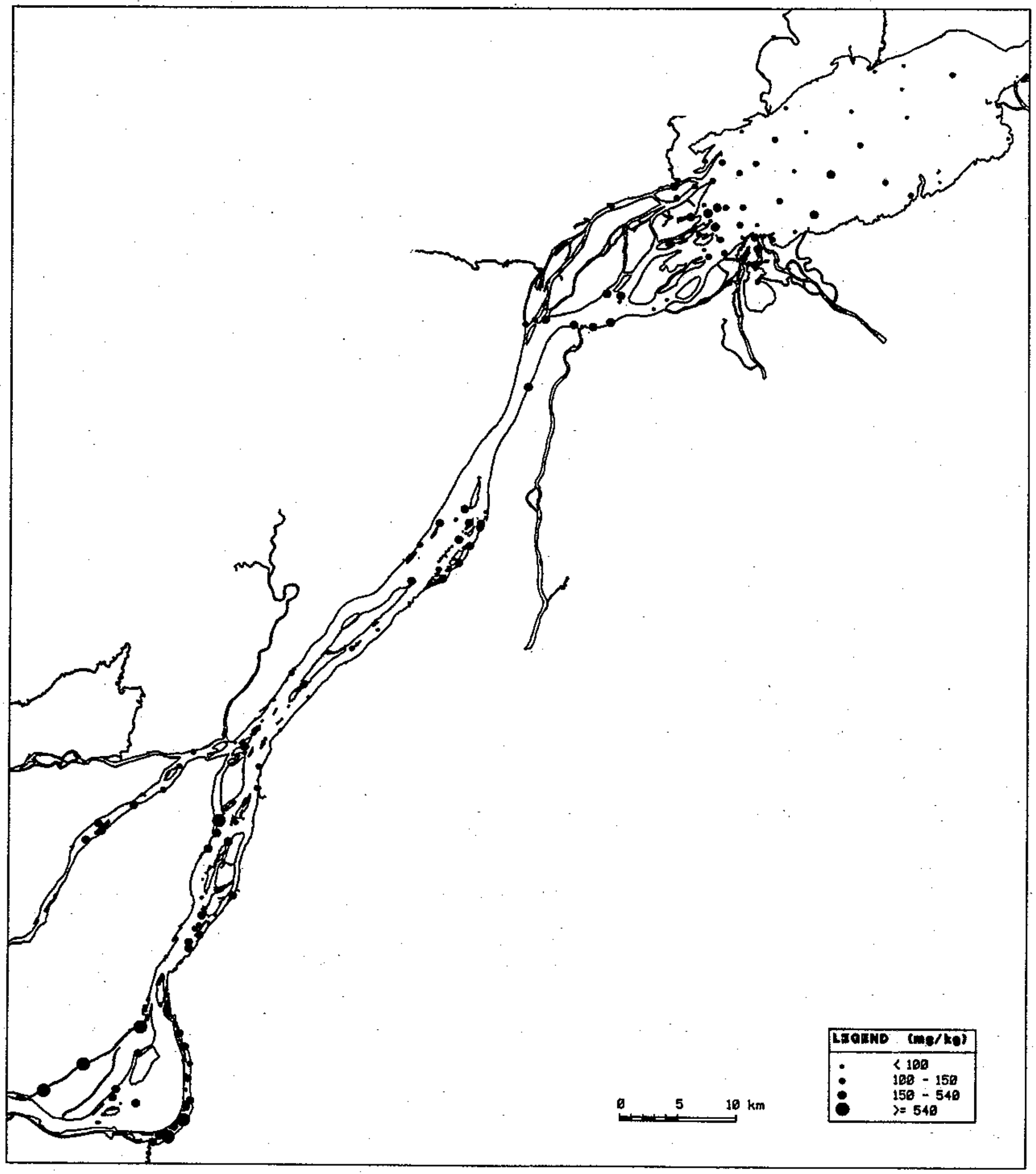


Figure 44 **Zinc distribution in sediment between the La Prairie basin and Pointe du Lac (1976)**

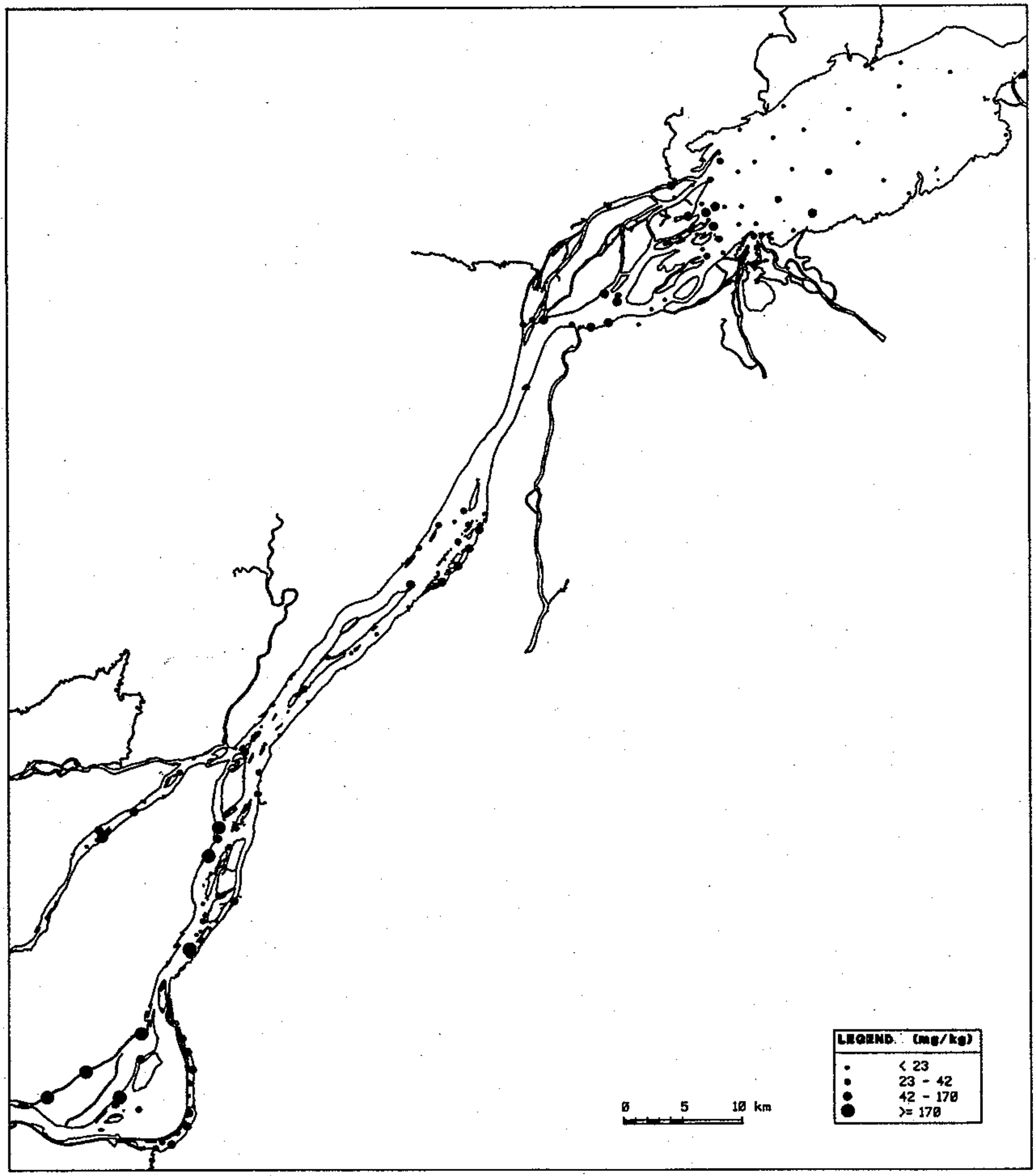


Figure 45 ***Lead distribution in sediment between the La Prairie basin and Pointe du Lac (1976)***

In Lake St. Pierre, moderate lead enrichment was detected at the mouth of the Richelieu River, suggesting a local source of lead. Moderate enrichment was also detected at some stations in the Sorel delta. Elsewhere, concentrations were generally background levels.

The whole of subsystem 2b was found to be highly contaminated by cadmium (Figure 46). Medians for the lesser La Prairie basin, the Montréal-Sorel corridor and Lake St. Pierre were 9, 7 and 6 μg/g respectively--a slight downward trend upstream to downstream in the subsystem. The whole of subsystem 2b was as highly cadmium-contaminated as Lake St. Louis, Cornwall, the Lake St. Francis outlet and the St. Charles River, suggesting there is not just one source of cadmium contamination.

Subsystem 2b was on the whole moderately contaminated by chromium in 1976: median concentrations were 73, 61.6 and 71 μg/g in the lesser La Prairie basin, the Montréal-Sorel corridor and Lake St. Pierre respectively. Very high chromium concentrations were detected in Montréal harbour, in the Boucherville and Contrecoeur archipelagos, at the Sorel delta entrance, downstream of the mouth of the Richelieu River and of the Sorel-Tracy industrial complex, and upstream of Lake St. Pierre (Figure 47). Contamination of Lake St. Pierre decreased however upstream to downstream. Throughout the subsystem, highest concentrations were very often detected downstream of industrial or municipal outfalls that discharge chromium.

Nickel contamination was similar to chromium contamination in 1976. Median concentrations (48.4 μg/g in the lesser La Prairie basin, 32.6 μg/g in the Montréal-Sorel corridor and 32.7 μg/g in Lake St. Pierre) indicated moderate contamination of the lesser La Prairie basin and slight contamination of the downstream part of the subsystem. Contamination was comparable to that of Lake St. Francis and Lake St. Louis. The most contaminated areas were downstream of industrial outfalls that discharge nickel, especially in the Sorel-Tracy area (Figure 48).

A second survey was conducted in the lesser La Prairie basin and in Lake St. Pierre (Hardy et al., 1991a and 1991b) in 1986 and 1987. In 1989 and 1991, a quality survey of Montréal harbour was conducted (Environnement Illimité, 1990; Environnement

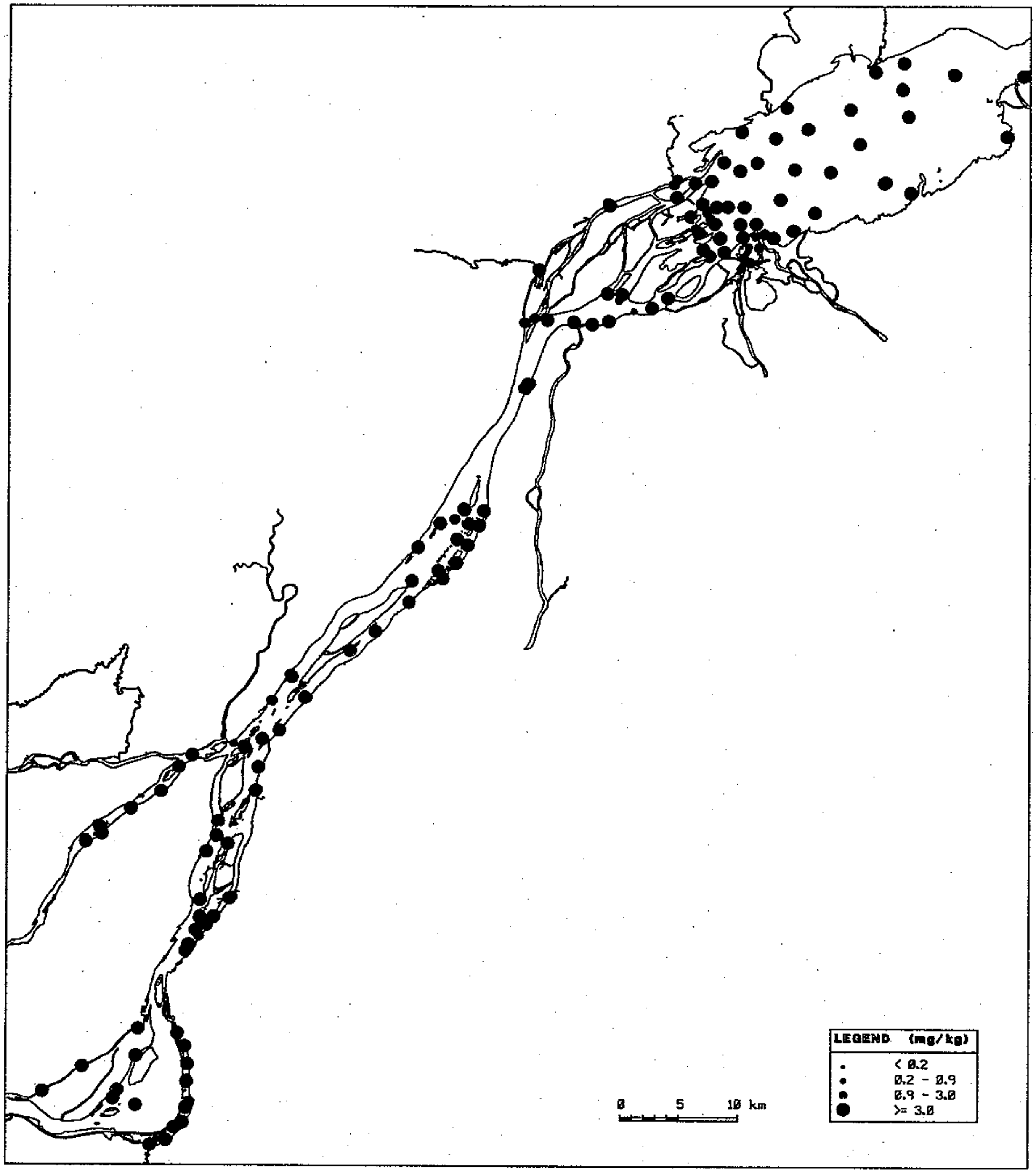


Figure 46 ***Cadmium distribution in sediment between the La Prairie basin and Pointe du Lac (1976)***

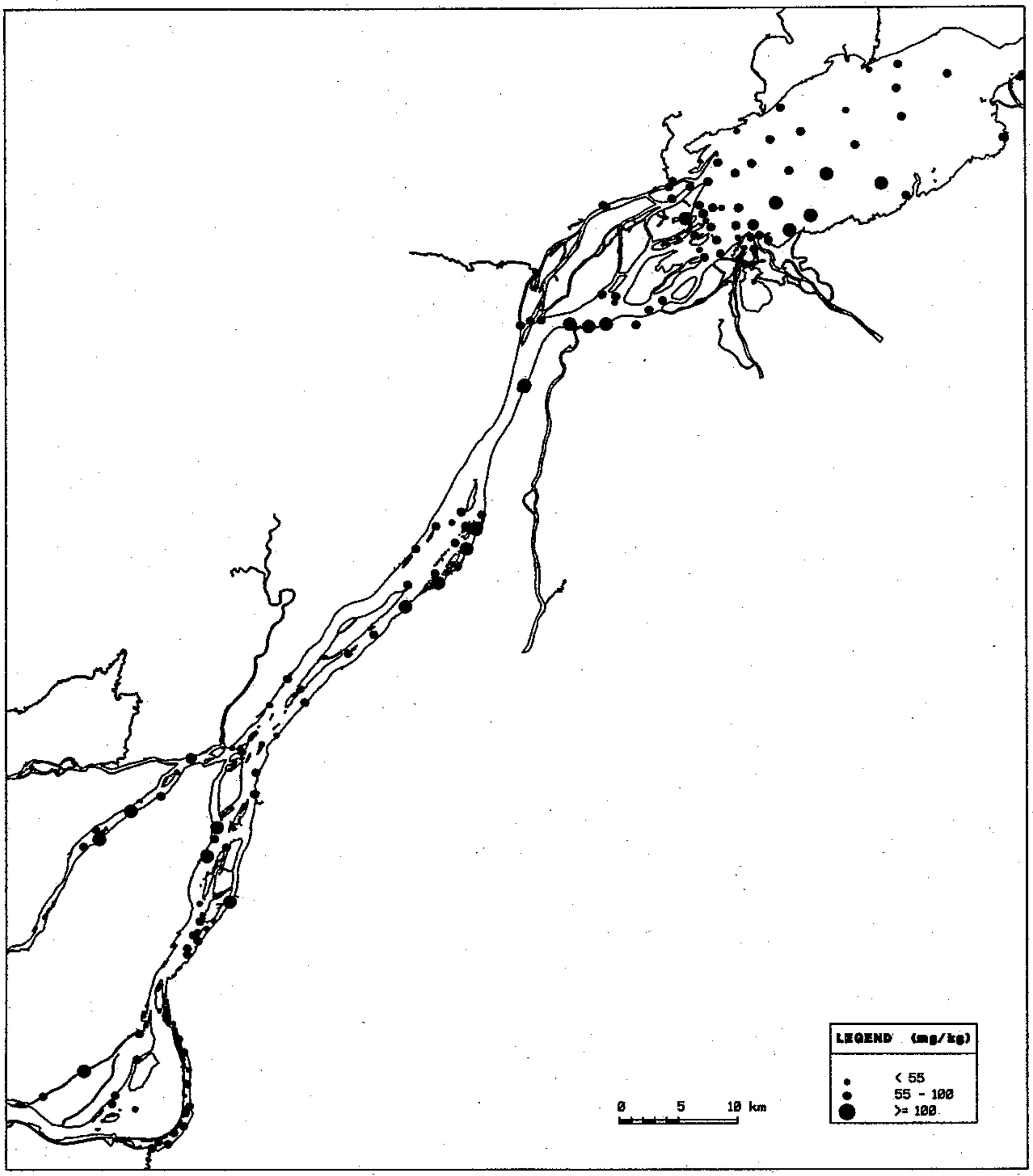


***Figure 47** Chromium distribution in sediment between the La Prairie basin and Pointe du Lac (1976)*

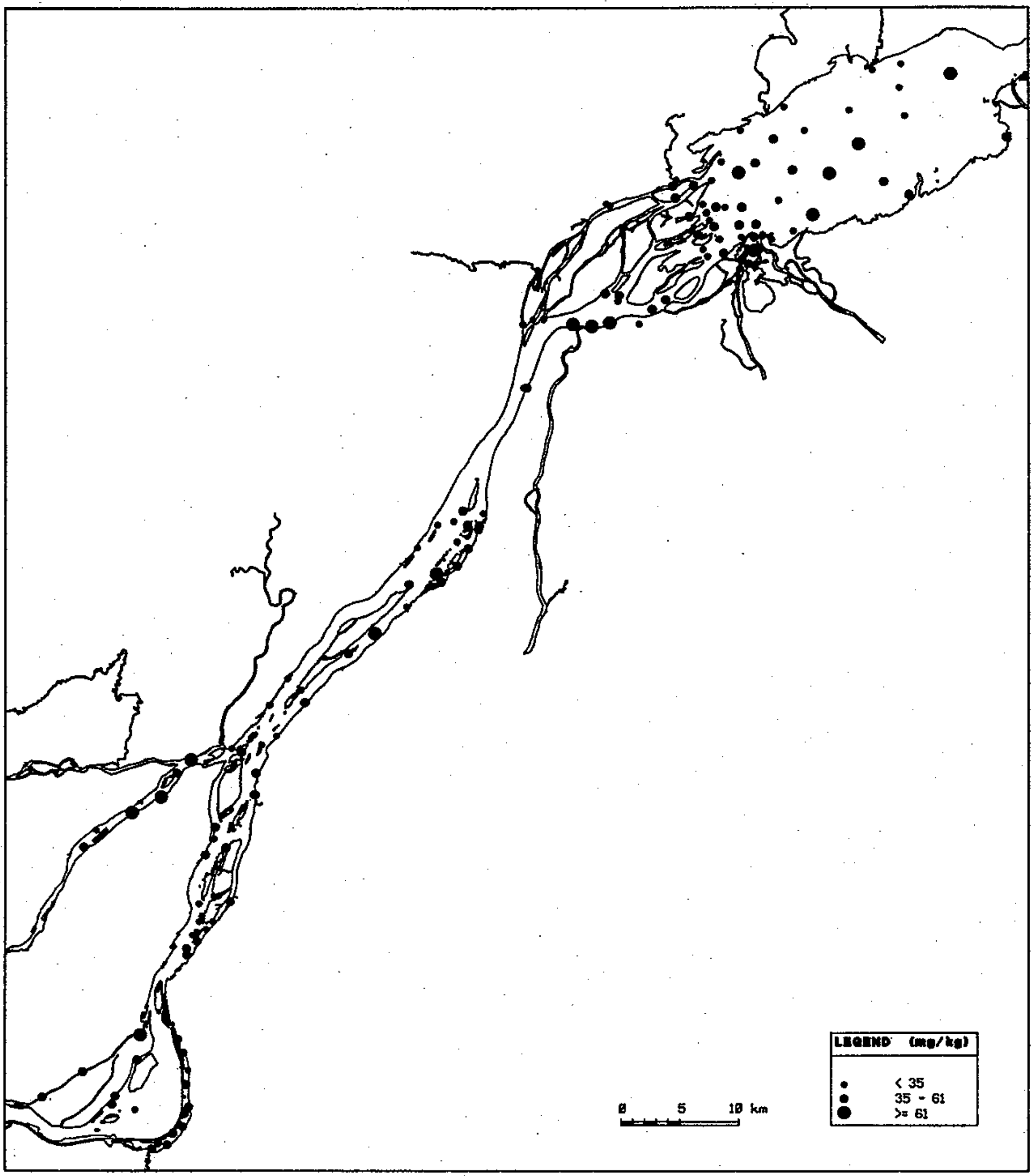


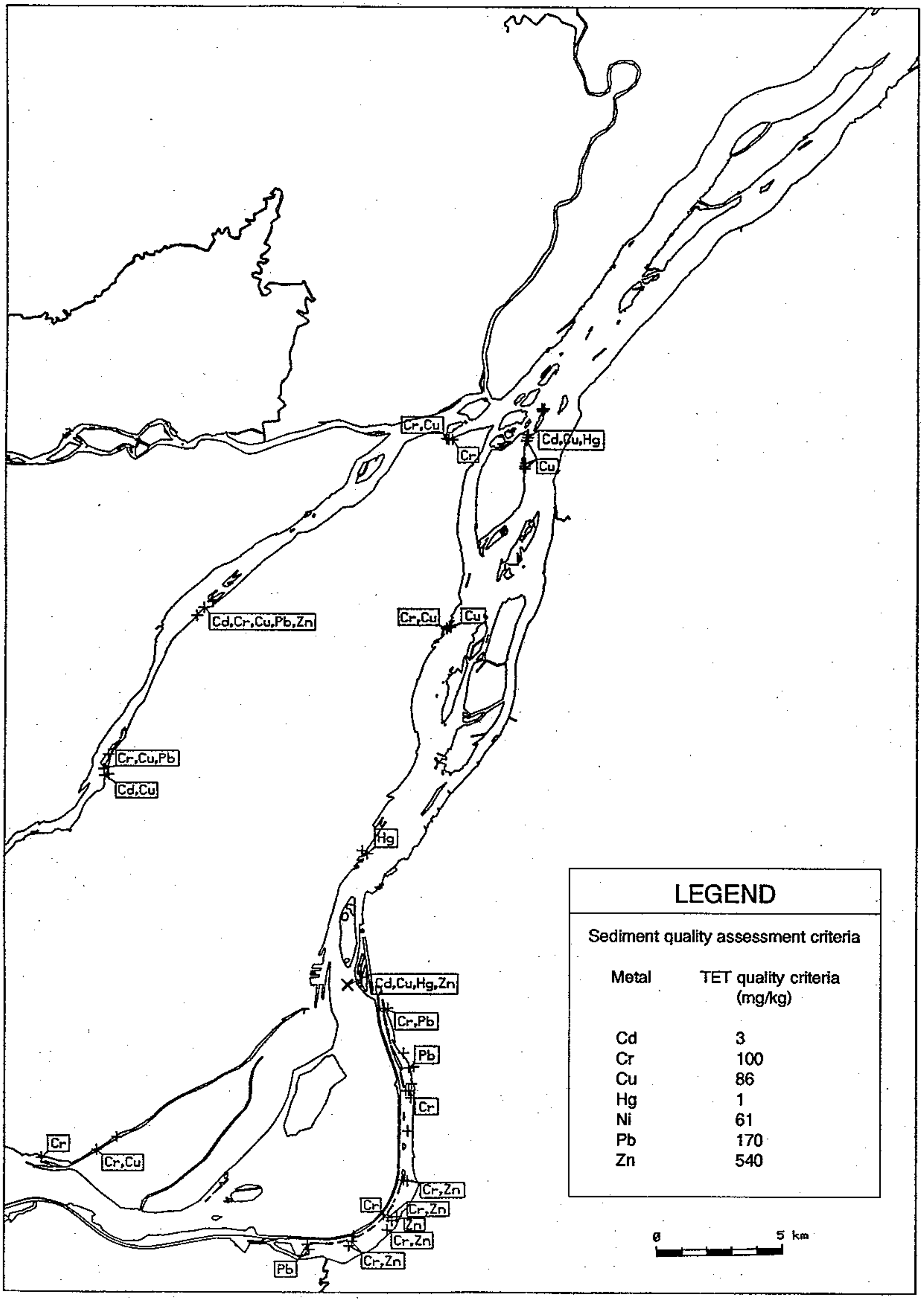
Figure 48 ***Nickel distribution in sediment between the La Prairie basin and Pointe du Lac (1976)***

Illimité and Lavalin Environnement, 1991). Data from the latter surveys were incompatible with the 1976 data however and could not be used for comparison: extractable rather than total metal fractions were analyzed, and only particles smaller than 64 μm were studied. The surveys did nonetheless show major contamination of certain basins by most heavy metals.

The surveys also showed mercury contamination of subsystem 2b did not diminish between 1976 and 1989. Mercury contamination of the lesser La Prairie basin remained moderate (median of 0.35 μg/g); and apart from the high concentrations at the basin entrance, mercury was distributed quite uniformly throughout the basin, suggesting its source may be upstream (figures 49 to 51). Median was comparable to that in Lake St. Louis during the period but higher than that in Lake St. Francis.

Between the Lachine rapids and Repentigny, mercury median was slightly higher in 1989 than in 1976. Mercury content of Montréal harbour sediment was also higher in 1989 than in 1976. At some harbour sampling stations major contamination was detected; maximum concentration (5.9 μg/g) was comparable to levels southeast of Îles de la Paix, an area known for mercury contamination. Trends in sediment quality between Repentigny and Sorel could not be identified because the area was not sampled recently. Despite slightly higher concentrations in the Sorel Islands and at the lake entrance, mercury levels remained low in the Sorel delta and Lake St. Pierre (median of 0.07 μg/g), though the Sorel delta was slightly more contaminated than the centre of the lake (medians of 0.1 and 0.03 μg/g respectively and maximum of 2.2 μg/g in the Sorel delta).

Copper contamination remained stable and moderate in the lesser La Prairie basin between 1976 and 1987 (medians of 55.3 and 62.9 μg/g respectively). Copper distribution pattern shows slightly higher concentrations in the centre of the basin than upstream or downstream (Figure 52), suggesting local sources play a major role in copper contamination. Local input of copper in 1989 came from two industrial plants (0.04 t/a), two tributaries (0.5 t/a) and two municipalities (0.1 t/a). Upstream input came mainly from



LEGEND	
Sediment quality assessment criteria	
Metal	TET quality criteria (mg/kg)
Cd	3
Cr	100
Cu	86
Hg	1
Ni	61
Pb	170
Zn	540

Figure 49 ***Exceedences of TET quality criteria between the La Prairie Bassin and Lavaltrie (1986-1987)***

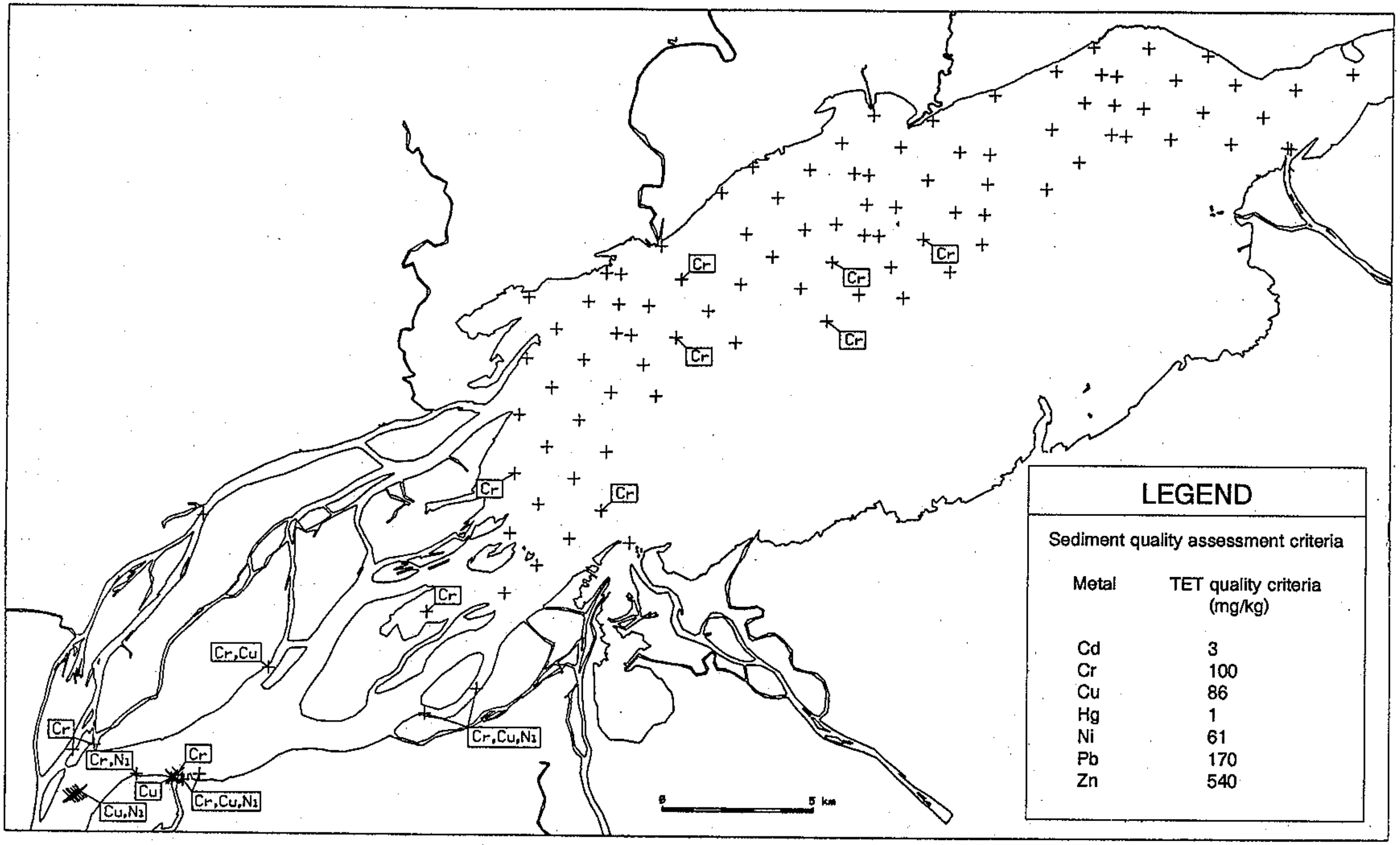


Figure 50 ***Exceedences of TET quality criteria in Lake St. Pierre (1986)***

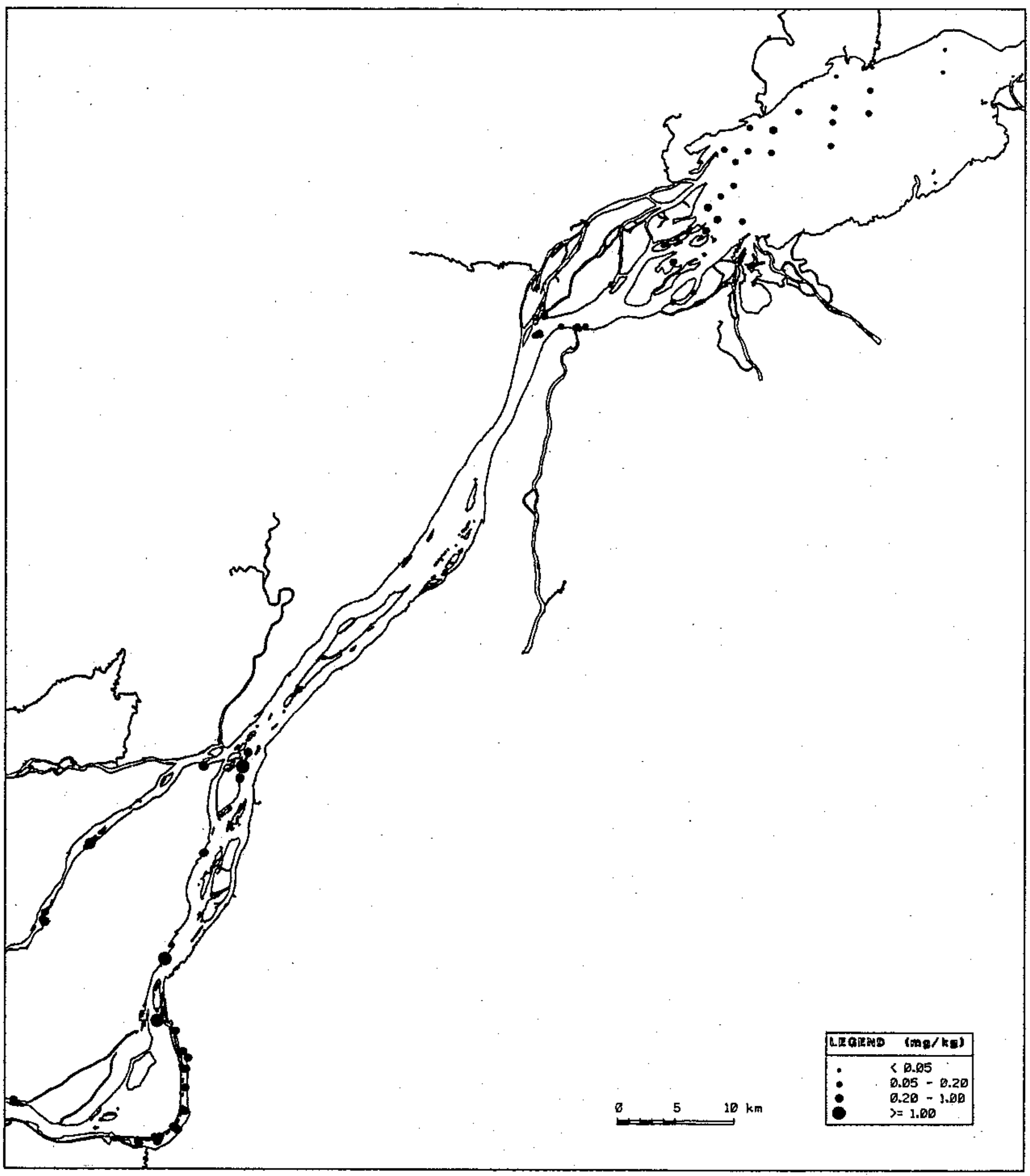


Figure 51 ***Mercury distribution in sediment between the La Prairie basin and Pointe du Lac (1986-1987)***

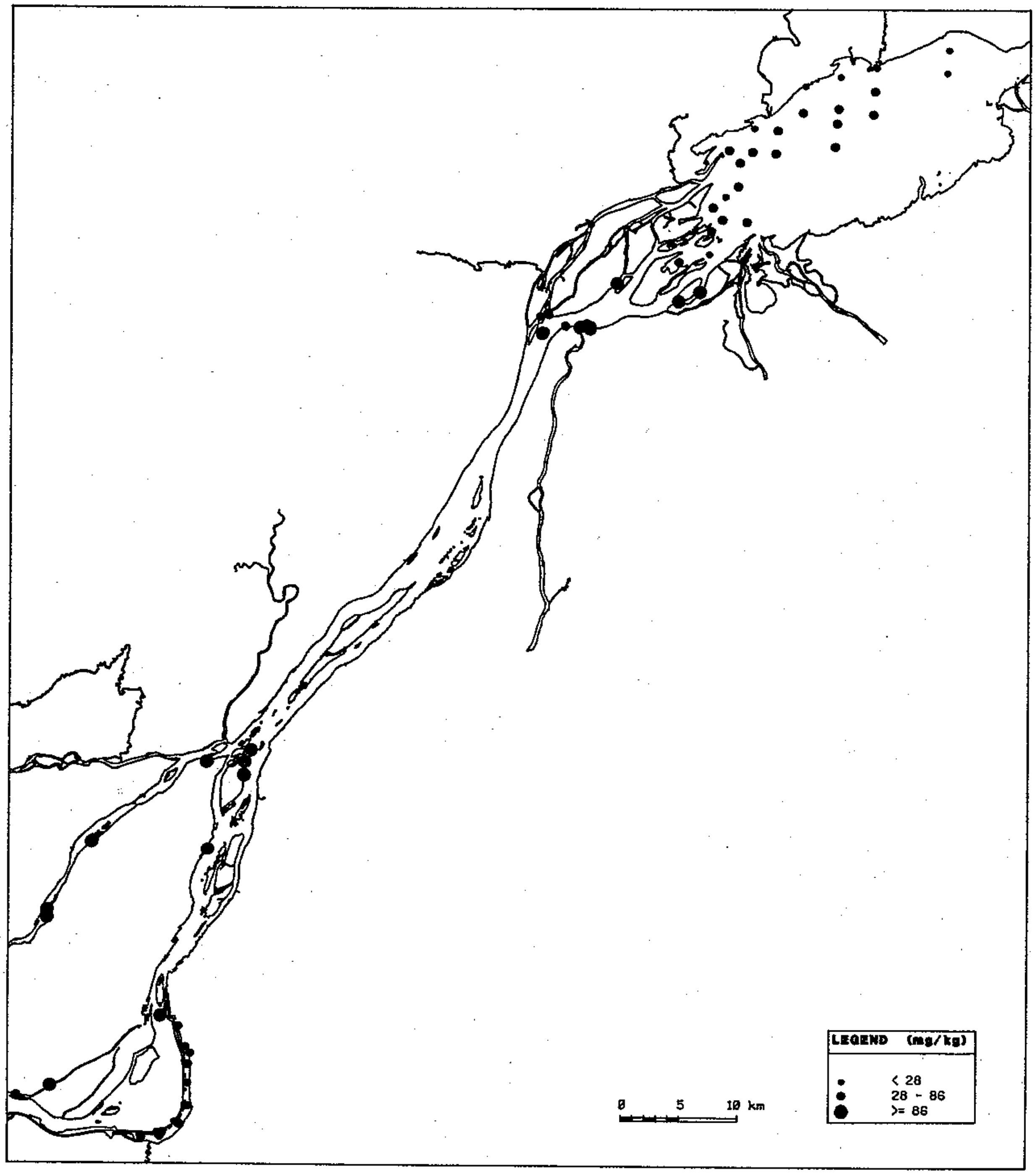


Figure 52 Copper distribution in sediment between the La Prairie basin and Pointe du Lac (1986-1987)

the Châteauguay River (4.7 t/a). The lesser La Prairie basin is more copper-contaminated than Lake St. Louis or Lake St. Francis; copper levels are low in both lakes.

Sediment quality data available for the Lachine-Repentigny area suggest major copper contamination of Montréal harbour in spots. Municipal discharges to this area continued through 1987, contributing an estimated 5 t/a of copper; the MUC's south collector and the treatment plants were not yet operational at the time of the survey. In addition, industrial plants (with Noranda Mines topping the list) were discharging 15 t/a of copper to the area. Copper input from upstream reaches of the St. Lawrence River was estimated at more than 315 t/a (Asseau, 1992b).

High levels of copper were found in sediment south of the Sorel delta. Upstream of the mouth of the Richelieu River, copper contamination is mainly attributable to input from upstream reaches of the St. Lawrence River (close to 700 t/a). The two main local sources of copper are the Richelieu River (close to 600 t/a) and a plant operated by QIT - Fer et Titane (150 t/a). The Richelieu River ranks second for copper input among the tributaries of the St. Lawrence River, and the QIT - Fer et Titane plant contributes more copper to the St. Lawrence River than any other industrial plant. These two sources of copper have a major impact on contamination of sedimentation sites downstream of the Richelieu River. This part of the St. Lawrence River corridor appeared to be more contaminated in 1987 than in 1976 (median was 35.9 μg/g in 1976 compared to 89.3 μg/g in 1987). The effect of the two sources of copper on sediment quality in the southern part of the lake could not be determined because property belonging to the Department of National Defence was not sampled.

Median concentrations of copper at sedimentation sites at the Lake St. Pierre entrance and in the central part of the lake also increased slightly over the decade but never became alarming; contamination remained moderate (medians of 46.2 and 31.2 μg/g respectively). Distribution pattern suggests the contamination stems mainly from upstream input.

Median concentration of zinc in the lesser La Prairie basin increased between 1976 and 1987 (from 315 to 392 μg/g). Highest concentrations were detected immediately downstream of the Candiac outfall (Figure 53). This outfall, which receives effluents from Locweld and Perkins Papers as well as wastewater from the municipality of Candiac, contributed a total of 0.2 t of zinc in 1989. Although contamination of the lesser La Prairie basin as a whole was moderate, zinc levels are a good deal higher in the basin than in Lake St. Louis (179 μg/g) and Lake St. Francis (125 μg/g). Apart from the Candiac outfall, the main source of zinc seems to be upstream reaches of the St. Lawrence River (estimated input is 317 t/a, of which 11 t/a are contributed by the Châteauguay River).

There are not enough data on the Montréal-Sorel corridor to make historical comparisons; data available do however show moderate zinc contamination at the old power plant in Verdun and in Montréal harbour.

Zinc enrichment of the Sorel delta was generally moderate (234 μg/g), possibly due to major input from Rivière des Prairies and Rivière des Mille Îles (estimated at 1000 t/a by Asseau, 1992b). Slight zinc contamination was detected at the mouth of the Richelieu River and upstream of Lake St. Pierre in 1987; an increase over zinc levels detected in 1976. Median concentrations of zinc in the Sorel delta, the upstream part of the lake and the centre of the lake rose from 124, 108 et 86 μg/g respectively in 1976 to 234, 136 and 121 μg/g in 1987. Contamination level of the Lake St. Pierre is between that of Lake St. Francis and that of Lake St. Louis. Among the major known zinc sources which may have affected sediment in the Montréal-Sorel corridor and the upstream part of Lake St. Pierre are upstream reaches of the St. Lawrence River (742 t/a at Lanoraie), the Richelieu River (592 t/a), QIT - Fer et Titane (close to 140 t/a) and the St. Francis River (150 t/a) (Asseau, 1992b and 1992c).

Lead contamination of the lesser La Prairie basin increased between 1976 and 1987. Median concentration rose from 48 to 137 μg/g; this is moderate contamination. Highest concentrations were detected at the lesser La Prairie basin entrance in 1987 (Figure 54), suggesting the contamination comes mainly from upstream. The main

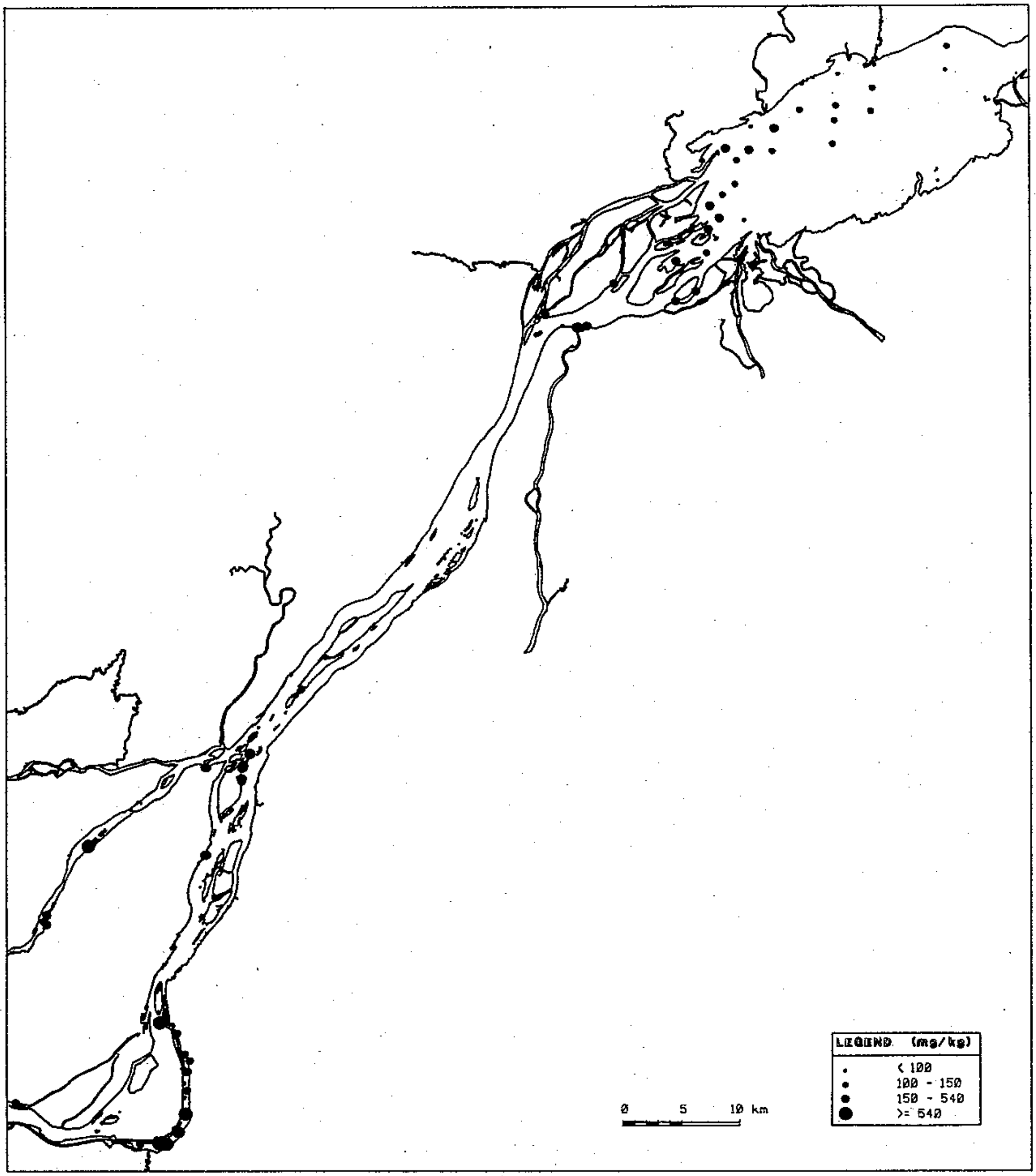


Figure 53 Zinc distribution in sediment between the La Prairie basin and Pointe du Lac (1986-1987)

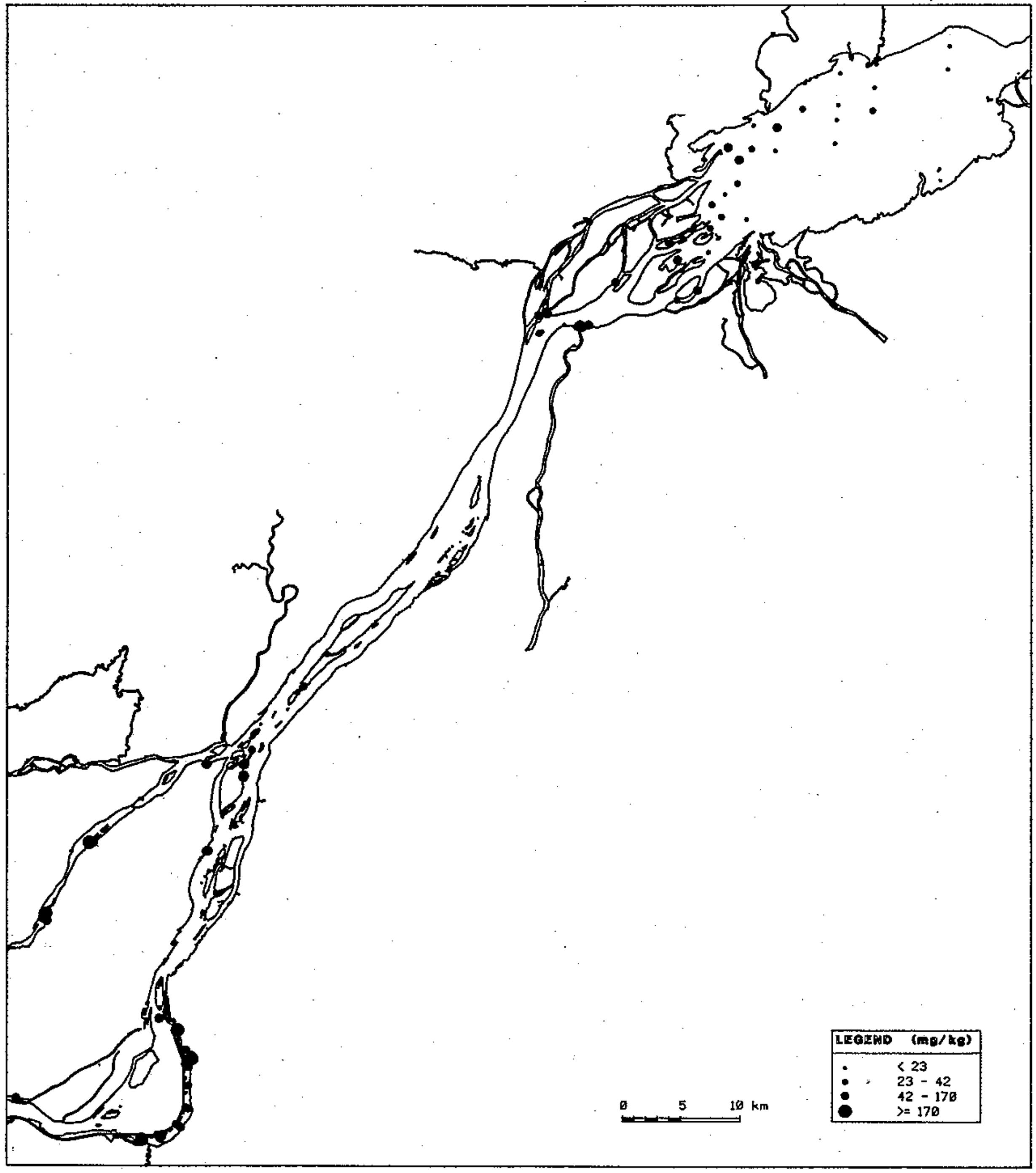


Figure 54 ***Lead distribution in sediment between the La Prairie basin and Pointe du Lac (1986-1987)***

upstream source of lead is the Châteauguay River (70 t/a); the plume of the Châteauguay River runs along the south shore and flows into the lesser La Prairie basin. Asseau (1992b) estimated the Châteauguay River contributes 70 t/a to the subsystem, that is, three times more lead than other subsystem tributaries and 20 percent more than upstream reaches of the St. Lawrence River. Local sources of contamination were minimal compared to the Châteauguay River. Asseau (1992b) and Hardy et al. (1991a) mention the following sources nonetheless: the St. Jacques River (0.3 t/a), Rivière de la Tortue (0.2 t/a), the St. Régis River (0.1 t/a) and the four municipal outfalls--Candiac, La Prairie, Lemoyne and Ste. Catherine (total input of 0.3 t/a) (Asseau, 1992b).

Median concentration of lead is substantially higher in the lesser La Prairie basin than in Lake St. Louis or Lake St. Francis. Despite the deterioration, contamination was moderate in 1987.

There are not enough data available on lead contamination of the Montréal-Sorel corridor for historical comparison. The data that are available and the sediment characterizations for the Montréal harbour restoration program indicate, nonetheless, that parts of the corridor are highly contaminated by lead, especially one part of Montréal harbour (Environnement Illimité, 1990; Environnement Illimité and Lavalin Environnement, 1991). The contamination stems from municipal discharges (26 t/a), local industrial plants (3 t/a), tributaries (175 t/a) and upstream sources (158 t/a).

In the Sorel delta and Lake St. Pierre, lead concentrations were higher in the 1980s than in 1976; though median concentration rose from 25 to 52.3 μg/g over the decade, the area nevertheless remained only slightly lead contaminated. Distribution pattern of lead was similar to that of zinc: highest concentrations were south of the delta, at the mouth of the Richelieu River. Median concentrations decreased between the Sorel delta (52.3 μg/g) and the centre of the lake (18.7 μg/g), suggesting the major local sources of lead--the Richelieu River (100 t/a) and QIT -Fer et Titane (15 t/a)--are the main contaminators of sediment in this part of the Sorel delta. Other sources--topping the list are upstream reaches of the St. Lawrence River (215 t/a) followed by the St. Francis River

(80 t/a)--contributed significantly to lead enrichment throughout the lake. Overall, lead contamination of Lake St. Pierre (30 μg/g) was comparable to that of Lake St. Francis (24,2 μg/g) and Lake St. Louis (36 μg/g).

Median concentration of cadmium in the lesser La Prairie basin in 1989 (<1 μg/g) shows there has been a big improvement in sediment quality since 1976 (median of 9 μg/g) (Figure 55). Pattern of spatial distribution of cadmium in the basin could not be determined, however, because of the high detection limit selected (1.00 μg/g). Known cadmium sources that may have affected the basin are the industrial area southeast of Lake St. Louis (0.8 t/a) and the St. Jacques River (0.02 t/a) (Asseau, 1992b and 1992c).

Major cadmium contamination was detected in Montréal harbour. Cadmium contamination in Lake St. Pierre decreased over the decade; median concentration dropped from 6 μg/g in 1976 to <1 μg/g in 1986. As in the lesser La Prairie basin, distribution pattern could not be determined because of the high detection limit. Known local sources of cadmium are the tributaries and certain industrial plants (Asseau, 1992b and 1992c).

Chromium contamination of the lesser La Prairie basin increased significantly between 1976 and 1986; median concentration rose from 73 to 105 μg/g. The basin is highly contaminated by chromium (Figure 56), the contamination exceeding that of Lake St. Louis (72 μg/g) and that of Lake St. Francis (35 μg/g). Chromium concentrations were higher in the middle of the basin than at either end, a distribution pattern that suggests local sources are mainly responsible for the contamination. Montréal harbour is highly contaminated by chromium in spots.

Chromium contamination of Lake St. Pierre sediment also increased between 1976 and 1986; median concentration of chromium rose from 71 to 100 μg/g. The upstream part of the Sorel delta, the mouth of the Richelieu River and the upstream part of Lake St. Pierre were all found to be highly contaminated by chromium in 1986. Contamination was worst right around the Sorel-Tracy industrial complex and in the plume of industrial effluents from this area.

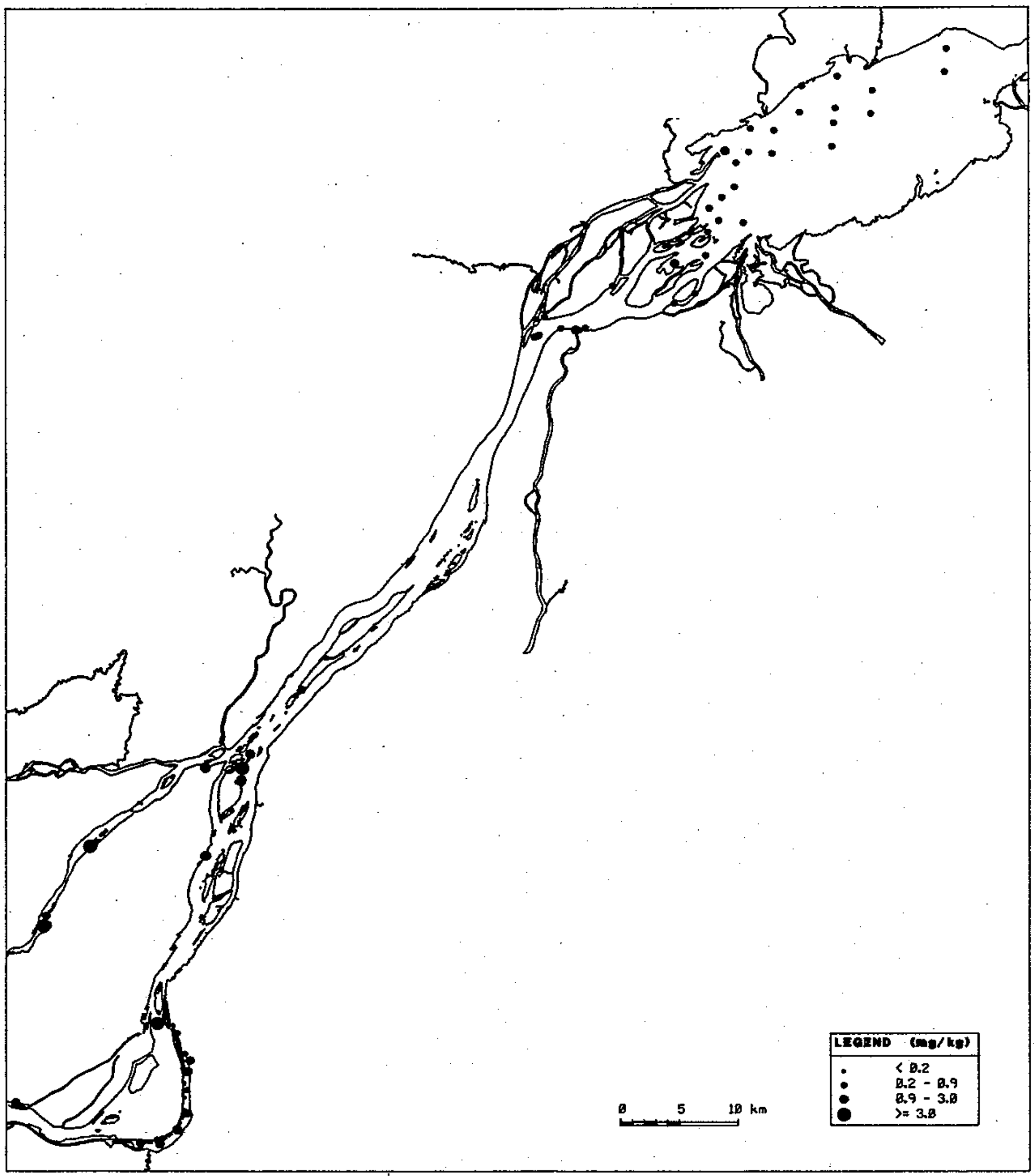


Figure 55 Cadmium distribution in sediment between the La Prairie basin and Pointe du Lac (1986-1987)

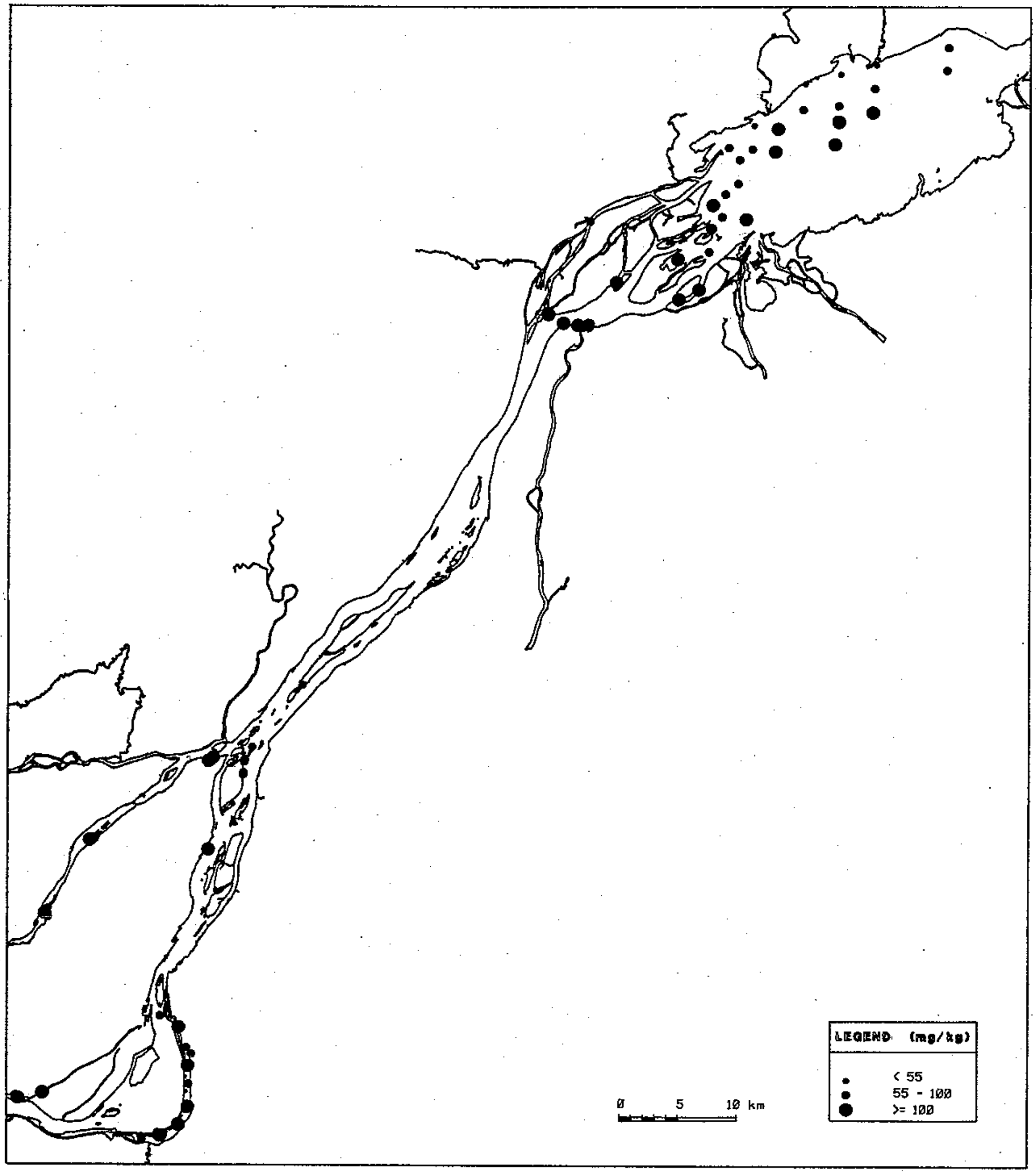


Figure 56 ***Chromium distribution in sediment between the La Prairie basin and Pointe du Lac (1986-1987)***

The QIT - Fer et Titane, Tioxide and Atlas Steel plants together discharged some 230 t of chromium to the subsystem in 1989; these plants contribute the highest industrial chromium input anywhere along the St. Lawrence River corridor (Asseau, 1992c). In addition, Kronos Canada in Varennes discharges close to 70 t/a of chromium. Local impact of the Kronos Canada input has not been measured recently; the Kronos Canada input may affect sediment quality in the Sorel delta. In 1986, Lake St. Pierre was more contaminated by chromium than Lake St. Louis or Lake St. Francis; a decade earlier, chromium contamination of Lake St. Pierre was comparable to that of Lake St. Louis.

Median concentration of nickel remained low in the lesser La Prairie basin between 1976 and 1987 (48.4 μg/g in 1976 and 41.1 μg/g in 1987). These medians are however higher than nickel medians in Lake St. Louis (35 μg/g) and Lake St. Francis (20.6 μg/g). Nickel distribution in the lesser La Prairie basin (Figure 57) suggests the main source of nickel may be upstream.

Environnement Illimité (1990) and Environment Illimité and Lavalin Environnement (1991) demonstrated Montréal harbour is contaminated by nickel. Highest nickel concentrations (103 μg/g) in subsystem 2b were detected in the downstream part of the subsystem, around the Sorel-Tracy industrial complex and in the plume of effluents from its industrial plants; this area is highly contaminated. Nickel concentrations were generally low however in the Sorel delta and in Lake St. Pierre. Nickel contamination level did not change in Lake St. Pierre over the decade (median was 32.7 μg/g in 1976 and 30.9 μg/g in 1986). Nickel contamination of Lake St. Pierre is comparable to that of Lake St. Louis (35 μg/g) but exceeds that of Lake St. Francis (20.6 μg/g).

Summary. Zinc, lead and chromium contamination of the lesser La Prairie basin increased appreciably between 1976 and 1987, cadmium contamination of the basin decreased and mercury, copper and nickel contamination remained stable. In other words, there was no uniform temporal contaminant distribution trend. During and just before the decade, no major measures were taken to significantly reduce input from local or upstream

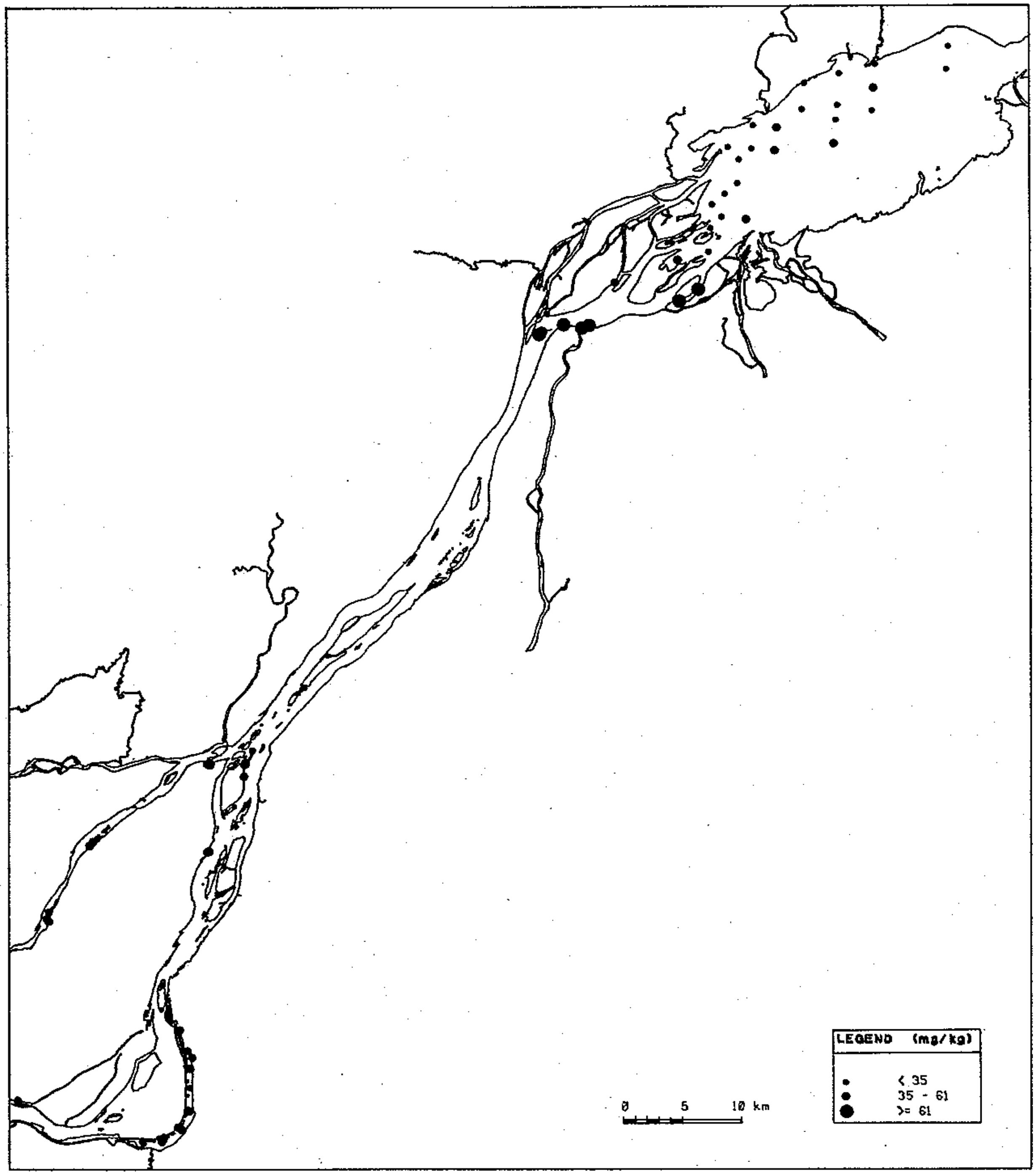


Figure 57 Nickel distribution in sediment between the La Prairie basin and Pointe du Lac (1986-1987)

sources apart from the reduction in industrial discharges to the Cornwall-Massena area (which is quite far upstream) and the decrease in certain types of input (mercury among others) to the Beauharnois area.

In 1987, the lesser La Prairie basin was moderately contaminated by trace metals and sediment quality at the mouth of the Candiac outfall was worse than anywhere else in the subsystem. Contaminant distribution patterns suggest that main sources of certain contaminants (mercury, lead, cadmium and nickel) are upstream, but that local sources play a major role with other contaminants (copper, zinc and chromium). Serious contamination was detected in Montréal harbour in 1976 as well as 1987.

The same trends were noted in the Sorel delta and Lake St. Pierre (in the downstream part of subsystem 2b) between 1976 and 1986 as in the lesser La Prairie basin. Zinc, lead and chromium contamination increased, cadmium contamination decreased and mercury, copper and nickel contamination remained stable. In 1986, Lake St. Pierre was on the whole slightly or moderately contaminated by trace metals, depending on the metal. The southern part of the Sorel delta, the mouth of the Richelieu River and the part of the delta in the plume of Sorel-Tracy industrial effluents were much more contaminated than the rest of the lake by all the metals investigated with the exception of cadmium.

5 SEDIMENT QUALITY IN THE RIVERINE ESTUARY

5.1 Subsystem 3: Pointe du Lac to Île d'Orléans

5.1.1 Physiography and dynamics. The riverine estuary is 160 km long. It runs from the Lake St. Pierre outlet to the eastern tip of Île d'Orléans. It is a gently winding corridor generally 3 to 5 km wide. The main channel is a trough at least 10.5 m deep and 249 m wide. There are depressions downstream of Cap Santé (16 m) and near Québec City (60), Trois Rivières (21 m), Grondines (17 m) and Portneuf (33 m). There are also rapids around Deschambault and flats around Grondines, Cap Santé and Beauport. The main tributary of the riverine estuary is the St. Maurice River.

Between Lake St. Pierre and the Richelieu rapids, opposite Deschambault, tides cause currents to slow down and water level to rise. Downstream of the Richelieu rapids, current direction reverses completely throughout the entire flow section, even in hollows. Tidal range thus changes substantially along the riverine estuary: it is 0.3 m at Trois Rivières, 4 m at Portneuf and 6.5 m in the Québec City area. At low tide around the Richelieu rapids, flow is completely concentrated in the seaway channel.

Mean annual discharge at Québec City was 12 550 m^3/s between 1980 and 1988 (Table 34). Average residence time is a little over two days (four to five tidal cycles), since downstream of Portneuf to Île d'Orléans transit time is closely linked to tidal cycles and current reversal dynamics (Hydrotech, 1989).

At Île d'Orléans, 90 percent of the flow is concentrated in the south channel. Tide flow is zero at the Lake St. Pierre outlet, but averages 55 000 m^3/s at Île d'Orléans; total discharge is close to 70 000 m^3/s at Québec City (Hydrotech, 1989).

Table 35 shows mean annual tributary discharges. Annual, summer and spring discharges of the St. Maurice River are greater than those of any other subsystem tributary; the St. Maurice River contributes about 55 percent of annual tributary discharge to the Trois Rivières-Québec City stretch. Average discharges of the Rivière du Chêne and the Etchemin, Gentilly and St. Charles rivers are much smaller than those of the seven other tributaries; these rivers contribute no more than 4 percent of total tributary discharges to the subsystem.

Table 34 ***Mean annual discharge of the St. Lawrence River at Québec City between 1980 and 1988 (Environnement Québec, unpublished data)***

Year	Mean annual discharge (m^3/s)
1980	12 265
1981	13 181
1982	11 867
1983	12 955
1984	12 945
1985	12 723
1986	13 753
1987	11 903
1988	11 354
1989	--
Mean (1980-1988)	12 550

Boundary lines of the waters of the Great Lakes have been identified to within the vicinity of the Richelieu rapids, that is, the area where current reverses. Tributary waters run along the shoreline and then gradually mix more or less rapidly depending on local bathymetry, velocities and flows; between the Lake St. Pierre outlet and Deschambault the waters still divide into adjacent streams with different characteristics (conductivity and carbonates). The following streams are identifiable up to the Richelieu rapids:

Table 35 ***Tributary discharges between the Lake St. Pierre outlet and Québec City (Asseau, 1992d)***

Tributary	Discharge (m^3/s)
Etchemin River	24
Chaudière River	145
Rivière du Chêne	9.8
Gentilly River	5.5
Bécancour River	77
Nicolet River	61
St. Maurice River	725
Batiscan River	88
Ste. Anne River	78
Jacques Cartier River	85
St. Charles River	13
TOTAL	1311

Base years: 1985-1986

- Waters of the St. Maurice River
- Mixed waters of the St. Maurice, Ottawa and St. Lawrence (Great Lakes) rivers
- Mixed waters of the Ottawa and St. Lawrence (Great Lakes) rivers
- Waters of the St. Lawrence River (Great Lakes)
- Mixed waters of the Richelieu, St. Francis, Yamaska, Nicolet and St. Lawrence (Great Lakes) rivers

It is not until Batiscan, about 25 km downstream of the mouth of the St. Maurice River, that the waters of the St. Maurice River mingle with the mixed waters of the St. Maurice, Ottawa and St. Lawrence rivers. During low water, the waters of the Great Lakes spread out almost to the shoreline. During tributary flood periods, on the other hand, the mixed waters running along the shoreline spread out and push the waters of the Great lakes into the centre of the channel.

Downstream of Gentilly, diffusion dynamics are even more complex: here tides are very strong, current reverses throughout the entire flow section and velocities are fast because of the Richelieu rapids. At rising tide, opposing currents meet and streams mingle between the Richelieu rapids and Île d'Orléans. At high tide, however, opposing currents meet and streams mingle right at the Richelieu rapids. At ebb tide, streams of variable water quality partially reform.

Because of the tides, velocity regimes are complex and variable. Downstream of the Richelieu rapids, the encounter of river current and rising tide considerably slows velocities; ebb tide currents, however, speed up velocities. This occurs between Pointe du Lac and Deschambault too but is less intense. To add to it all, the Richelieu rapids speed up currents; and, like everywhere upstream, currents are fastest in the seaway channel. Maximum riverine estuary flow velocities are under the Québec City bridge.

Hydrotech (1989) estimates the St. Lawrence River annually transports some 4 800 000 t of suspended solids to Trois Rivières. To this must be added solid input from the St. Maurice (400 000 t/a), La Chaudière (340 000 t/a), Bécancour (about 190 000 t/a), Batiscan (about 170 000 t/a) and Ste. Anne (about 110 000 t/a) rivers and the combined input of other tributaries (about 242 000 t/a). The St. Lawrence River transports some 6 252 000 t/a of sediment from tributaries and from the international section of the river to Québec City.

One unusual feature of this stretch is that the Bécancour and Portneuf docks divert bottom material into the seaway channel, where it continues on downstream.

5.1.2 Sources of contamination

Industrial discharges. The following information on toxic input comes from Asseau (1992d). There are ten targeted plants in the subsystem. Four are in the Trois Rivières area, close to the mouth of the St. Maurice River (Kruger Inc., Canadian Pacific Forest Products Ltd., Stone Consolidated Inc. (Wayagamak Division) and the Reynolds Aluminium Company of Canada Ltd) and two are in Becancour (Aluminerie de Bécancour

Inc. and ICI Canada Inc). Domtar Inc. operates a plant much further downstream, at Donnacona; Daishowa Inc. has facilities in Québec City; Ultramar Canada Inc. has a plant at Lévis; and Abitibi Price Inc. has facilities in Ste. Anne de Beaupré. Of the ten plants, six are pulp and paper mills, two are metallurgy plants, one is an inorganic chemicals plant and one is a petrochemical plant.

Kruger Inc. operates a pulp and paper mill in Trois-Rivers that converts logs, chips and kraft pulp into newsprint and coated paper. The plant has three outfalls, one of which discharges rainwater and process water to the St. Lawrence River at a rate of about 0.91 m^3/s.

Canadian Pacific Forest Products Ltd. owns a mill in Trois Rivières. Until it closed down in 1992, the mill produced cardboard, newsprint and specialty paper from kraft pulp and logs using sodium hydrosulphite to bleach the pulp and sodium bisulphite to pulp the chips. The mill has three outfalls: one discharged process water and sanitary sewage to the St. Lawrence River at a rate of 0.95 m^3/s and the other two emptied into a sedimentation basin.

Stone Consolidated Inc. (Wayagamak Division) owns a mill in Trois Rivières that manufactured newsprint and kraft paper from logs and wood chips until it closed down several years ago. The mill evacuated process water, rainwater and sanitary sewage through seven outfalls that discharged to the St. Maurice River (total discharge was 0.87 m^3/s).

Reynolds Aluminum Company of Canada operates a secondary aluminium treatment plant at Cap de la Madeleine that also converts the treated aluminum to aluminium paper and packaging products. Wastewater is evacuated through two outfalls connected to the municipal sewer system; total discharge of the two outfalls is 0.016 m^3/s.

Aluminerie de Bécancour Inc. (ABI) operates a metallurgy plant in Bécancour that manufactures aluminum ingots, billets and plates from alumina. Two outfalls connected to the municipal system evacuate sanitary sewage. A third outfall discharges process water, rain water and cooling water to the St. Lawrence River.

ICI Inc. operates an inorganic chemicals plant in Bécancour that manufactures caustic soda and hydrochloric acid from HCL salt. The plant has a single outfall that discharges process water, cooling water and rainwater to the St. Lawrence River at an average rate of 0.057 m^3/s.

Domtar Inc. operates a mill in Donnacona that produces newsprint and insulating board from chips, cardboard discards and paper discards. The mill has a single outfall that empties into the city's main sewer at a rate of 0.43 m^3/s.

Daishowa Inc. operates a mill in Québec City that converts logs and wood chips to cardboard, newsprint and chemical pulp. The mill has a single outfall that empties into the Québec Urban Community diffuser at a rate of 1.63 m3/s.

Ultramar Canada Inc. owns facilities in St. Romuald that convert crude oil into a wide range of petroleum products including unleaded gasoline, diesel fuel and fuel oil. The facilities have two outfalls: one discharges process water and rainwater to the St. Lawrence River at a rate of 0.074 m^3/s and the other is only active when it rains.

Abitibi Price Inc. operates a mill in Beaupré that manufactures specialty paper from kraft pulp, logs and wood chips. The mill has a single combined outfall that discharges process water, sanitary sewage and rainwater to the St. Lawrence River at a rate of 0.38 m^3/s.

Table 36 shows daily input of the three metals measured in effluents from the industrial plants described above.

Since so few measurements were available, it was not possible to compare input contributed by each effluent.

Tributaries. Table 37 summarizes toxic input of five reference metals from eleven subsystem tributaries: Rivière du Chêne and the Batiscan, Bécancour, Chaudière, Etchemin, Gentilly, Jacques Cartier, Nicolet, St. Charles, St. Maurice and Ste. Anne rivers.

Table 36 ***Industrial metal input (Cu, Zn and Cr) between Pointe du Lac and Île d'Orléans (Asseau, 1992d)***

Metal	1	2	3	4	5	6	7	8	9
Copper (kg/d)				0.75					
Zinc (kg/d)	1.6			13.3					
Cr^{+6} (kg/d)	2.9								

Base year: 1989 Inaccuracy of input: about 30%

Legend
1. I.C.I. Inc.
2. Canadian Pacific Forest Products Ltd.
3. Stone Consolidated Inc. (Wayagamak Division)
4. Kruger Inc.
5. Aluminerie de Bécancour Inc.
6. Reynolds Aluminum Co. of Canada
7. Domtar Inc.
8. Ultramar Canada Inc.
9. Abitibi Price Inc.

The St. Maurice River tops the list of contributors of toxic input (50 percent of total subsystem tirbutary input) for almost all metals because its shoreline is industrialized and its discharge substantial. This river also contributes more toxic input to the St. Lawrence River than any other St. Lawrence tributary. Contributions of other tributaries to total tributary toxic input to the subsystem are as follows: Nicolet River, 9.1 percent; Ste. Anne River, 8.4 percent; Chaudière River, 7.7 percent; Bécancour River, 7.3 percent; Batiscan River, 6.2 percent; Jacques Cartier River, 4.9 percent; St. Charles River, 2.3 percent; Du Chêne River, 1.4 percent; and Gentilly River, 1.1 percent.

Daily copper input of the St. Maurice River constitutes 86 percent of copper input from all subsystem tributaries. In fact, the St. Maurice River contributes more copper to the St. Lawrence River than any other tributary of the river. The Chaudière and Bécancour rivers make the second and third highest copper contributions to the riverine estuary, 4.1 and 3.4 percent of total input respectively. Contributions of other tributaries do not exceed 1.5 percent (45 kg/a) of total tributary copper input to the subsystem.

Table 37 ***Tributary metal (Cu, Zn, Pb, Fe and Cd) input between Pointe du Lac and Île d'Orléans (Asseau 1992d)***

River	Cu (kg/d)	Zn (kg/d)	Pb (kg/d)	Fe (kg/d)	Cd (kg/d)
Etchemin River	13	12	16	913	2.1
Chaudière River	113.3*	403.7*	97.3	3 211	13
Rivière du Chêne	4.4	16	17	685	0.90
Gentilly River	2.0	3.6	4.2	554	0.50
Bécancour River	94.1*	272.2*	50.1*	3 312	6.7
Nicolet River	31.8*	113.2*	411.1*	4 047	14
St. Maurice River	2 353.6*	1 292.7*	475.3*	21 496	63
Batiscan River	21	65	57	3 059	7.7
Ste. Anne River	41*	171*	510*	3 674	6.8
Jacques Cartier River	41	76	55	2 360	7.4
St. Charles River	17	19	14	1 111	1.2
TOTAL	2 732.2	2 444.4	1 707	44 422	123.3

Base years: 1985-1986
Inaccuracy of input: 25 to 45%
* These values incorporate input of municipalities along the tributary downstream of the gauging station.

The St. Maurice River also contributes a lot of zinc--53% of total tributary zinc input to the subsystem. In fact, the St. Maurice River contributes more zinc than any other tributary along the Lawrence River corridor apart from Rivière des Prairies. Contributions of other tributaries to total tributary toxic input to the subsystem are as follows: Chaudière, 17 percent; Bécancour, 11 percent; Ste. Anne, 7.0 percent; Nicolet, 4.6 percent; Jacques Cartier, 3.1 percent; and Batiscan, 2.7 percent. Each of the other tributaries contributes less than 1 percent of total tributary zinc input. In the riverine estuary, spring zinc load is three times summer zinc load.

The Ste. Anne River contributes more lead than any other subsystem tributary (30 percent). Two other rivers also contribute substantial loads: the St. Maurice River (28 percent) and the Nicolet River (24 percent). These three rivers contribute more lead to the St. Lawrence corridor than any other St. Lawrence tributary. In the riverine estuary, spring lead load is almost four times summer load.

The St. Maurice River contributes more cadmium to the St. Lawrence corridor than any other St. Lawrence tributary. Cadmium input of the St. Maurice River constitutes 51 percent of tributary input to the riverine estuary. Spring cadmium load is two and a half times summer load.

Municipalities. Table 38 shows subsystem municipal input measured in 1989. Municipalities contributed a total of 15.5 kg/d of copper, 60.9 kg/d of zinc and 29.7 kg/d of lead. Most of the input (96 percent) came from the Québec Urban Community (QUC), which drains wastewater generated by the area's largest community (475 000 people). QUC input was however less than a third of municipal input south of Montréal Island. Other municipalities discharge negligible loads compared to those of the QUC. Zinc topped the list of contaminants, followed by lead and then copper.

Upstream St. Lawrence River reaches. Input in 1989 from upstream reaches of the St. Lawrence River was estimated from water quality data obtained at three reference stations forming a north-south transect at Laviolette bridge in Trois Rivières and from mean monthly discharge data for 1989. Input was calculated by multiplying monthly input by the portion of flow corresponding to the measuring station. Annual input at the station was obtained by adding up input for each of the twelve months. Annual input was calculated in this way for each of the three stations in the transect. Mean hydraulic regime of the St. Lawrence River in 1989 was however relatively low compared to regimes between 1981 and 1988; mean flow in 1989 was close to 1400 m^3 less than mean flows between 1980 and 1988, and spring runoff was particularly low in 1989. These differences may have caused underestimation of St. Lawrence River contaminant input compared to tributary input, for which the base year was 1985 to 1986.

Table 38 ***Municipal metal (Cu, Zn and Pb) input in 1989 between Pointe du Lac and Île d'Orléans (Asseau, 1992d)***

Municipality	Cu (kg/d)	Zn (kg/d)	Pb (kg/d)
Ste. Marthe	0.031	0.076	0.038
Champlain	0.008	0.021	0.011
Batiscan	0.008	0.022	0.011
St. Pierre les Becquets	0.013	0.034	0.017
Deschaillons sur le St. Laurent	0.018	0.046	0.023
Leclercville	0.005	0.013	0.006
Lotbinière	0.001	0.004	0.002
Deschambault	0.001	0.004	0.002
Cap Santé	0.013	0.033	0.017
Donnacona	0.038	0.095	0.047
Ste. Croix	0.029	0.073	0.036
St. Antoine de Tilly	0.014	0.035	0.018
Neuville	0.005	0.013	0.006
St. Nicolas	0.037	0.091	0.046
CUQ - west end	5.7	23.0	11.2
St. Romuald	0.016	0.41	0.20
St. David de L'Aube River	0.074	0.19	0.092
Lévis	0.31	0.77	0.39
CUQ - east end	8.8	35.5	17.32
Lauzon	0.21	0.52	0.26
TOTAL	5.4	61.0	29.7

Base year: 1989 Inaccuracy of input: 40 to 50%

Table 39 lists total estimated input of six metals at the three measuring stations.

More zinc (close to 1630 t) was transported by waters from upstream reaches of the St. Lawrence River in 1989 than any other metal, followed, in descending order, by chromium, copper, nickel, lead and cadmium. The metals are mainly transported through the centre of the seaway channel; metal input at the centre station ranges from 40 to 64 percent of transect total.

Table 39 ***Mean daily metal (Cu, Zn, Pb, Cd, Cr and Ni) input at three stations of the Trois Rivière transect (Asseau, 1992d)***

Metal	North (kg/d)	Centre (kg/d)	South (kg/d)	Total input (kg/d)
Cu	405	979	589	1 973
Zn	823	2 407	1 225	4 455
Pb	103	530	174	807
Cd	25	70	35	130
Cr	310	1 247	551	2 108
Ni	681	831	423	1 935

Base year: 1989
Minimum inaccuracy of upstream St. Lawrence River reaches input: 25%

Summary. Table 40 summarizes input from the four main sources of contamination between Pointe du Lac and Île d'Orléans. The main contributors of toxic input are clearly upstream reaches of the St. Lawrence river and subsystem tributaries; these sources contributed 99 percent of input of the three metals studied. Specifically, upstream reaches of the St. Lawrence River contributed 42 percent of copper load, 64 percent of zinc load and 32 percent of lead load in the subsystem. Tributaries are responsible for 58 percent of copper load, 35 percent of zinc load and 67 percent of lead load. The St. Maurice River is by far the leading contributor among subsystem tributaries.

Industrial and municipal input is minimal compared to that of tributaries and upstream St. Lawrence River reaches; industrial and municipal input ranges from 0.2 percent to 1.4 percent of total subsystem load depending on the contaminant. Though municipal and industrial sources contribute little to the toxic load of the riverine estuary, they may be responsible for local contamination.

Table 40 Annual metal (Cu, Zn and Pb) input from the four main sources of contamination between Pointe du Lac and Île d'Orléans (Asseau 1992d)

Source	Cu (kg/a)	Zn (kg/a)	Pb (kg/a)	%
Industrial plants	274	5 438	--	0.1
Tributaries	995 720	889 870	620 865	48.2
Municipalities	7 044	26 572	12 957	0.9
Upstream St. Lawrence River reaches	720 145	1 626 075	294 555	50.8
TOTAL	1 723 183	2 547 955	928 377	100

Inaccuracy of industrial input: 30%
Inaccuracy of tributary input: 25 to 45%
Inaccuracy of municipal input: 40 to 50%
Inaccuracy of upstream St. Lawrence River reaches input: 25%
-- Not available

Between the Lake St. Pierre outlet and downstream of Île d'Orléans, the St. Lawrence River receives total annual input of 1700 t of copper, 2500 t of zinc and 900 t of lead. Tributaries contribute the most copper, with the St. Maurice River topping the list at 86 percent of tributary input. Input from upstream reaches of the St. Lawrence river comes a close second. Municipal and industrial contributions are very small.

Upstream reaches of the St. Lawrence River are the main source of zinc; these waters input twice as much zinc as subsystem tributaries, which are the second major source of zinc. Tributary input comes mainly from the St. Maurice (53 percent) and Chaudière (17 percent) rivers. Municipal and industrial zinc input is small.

Tributaries are the main source of lead. Lead input comes mainly from the Ste. Anne (30 percent), St. Maurice (28 percent) and Nicolet (24 percent) rivers. Tributaries contribute twice as much lead as upstream reaches of the St. Lawrence River. Municipal contribution is small and industrial contribution is not known.

5.1.3 Particle-size distribution. Figure 58 and Table 41 show dominant size fractions in the subsystem. The analysis that follows is based on data in the figure and table and on the work of Hydrotech (1989).

From the Lake St. Pierre outlet to the mouth of the Bécancour River, the channel bottom is coarse material or, less frequently, marine clay from the Champlain Sea. The mouth of the St. Maurice River and some of the right shore downstream of Île aux Sternes is conducive to sedimentation. Conditions along the left shore do not promote sedimentation. Downstream of the Bécancour dock, velocities speed up and bed material is predictably rock or a mixture of sand and gravel, readily transported to downstream of the Richelieu Rapids. A few flats appear starting at Gentilly, where current is slow. Composition of the flats varies with water energy level; they can be of silty sand, clayey silt or sandy clay.

Starting at Portneuf, channel bed material is sand, gravel and outcrops, and flats are of compacted clay. The estuary of the St. Charles River is dominated by silty sand, the Lévis nearshore by sandy silt, the Lauzon nearshore downstream of the shipyard by clayey silt and the north channel by sandy silt.

5.1.4 Physical chemistry. There has been little physicochemical characterization of the riverine estuary. The most exhaustive sampling was performed by the St. Lawrence River Study Committee (Sérodes, 1978). Since then, only specific areas have been sampled (the shipping channel, marinas, harbours and the vicinity of private docks) as needed for dredging or restoration projects. Accordingly, there is no single data set after 1976 that can be used to get an overall picture of the subsystem.

The Trois Rivières harbour was characterized in 1989 as part of the federal sites restoration program undertaken by Environment Canada's Environmental Protection Branch. The data collected (G.D.G. Environnement Ltée, 1990) could not however be used directly because they were incompatible with the data used for this report: extractable rather than total metal fractions were analyzed, and only particles smaller than 64 μm were

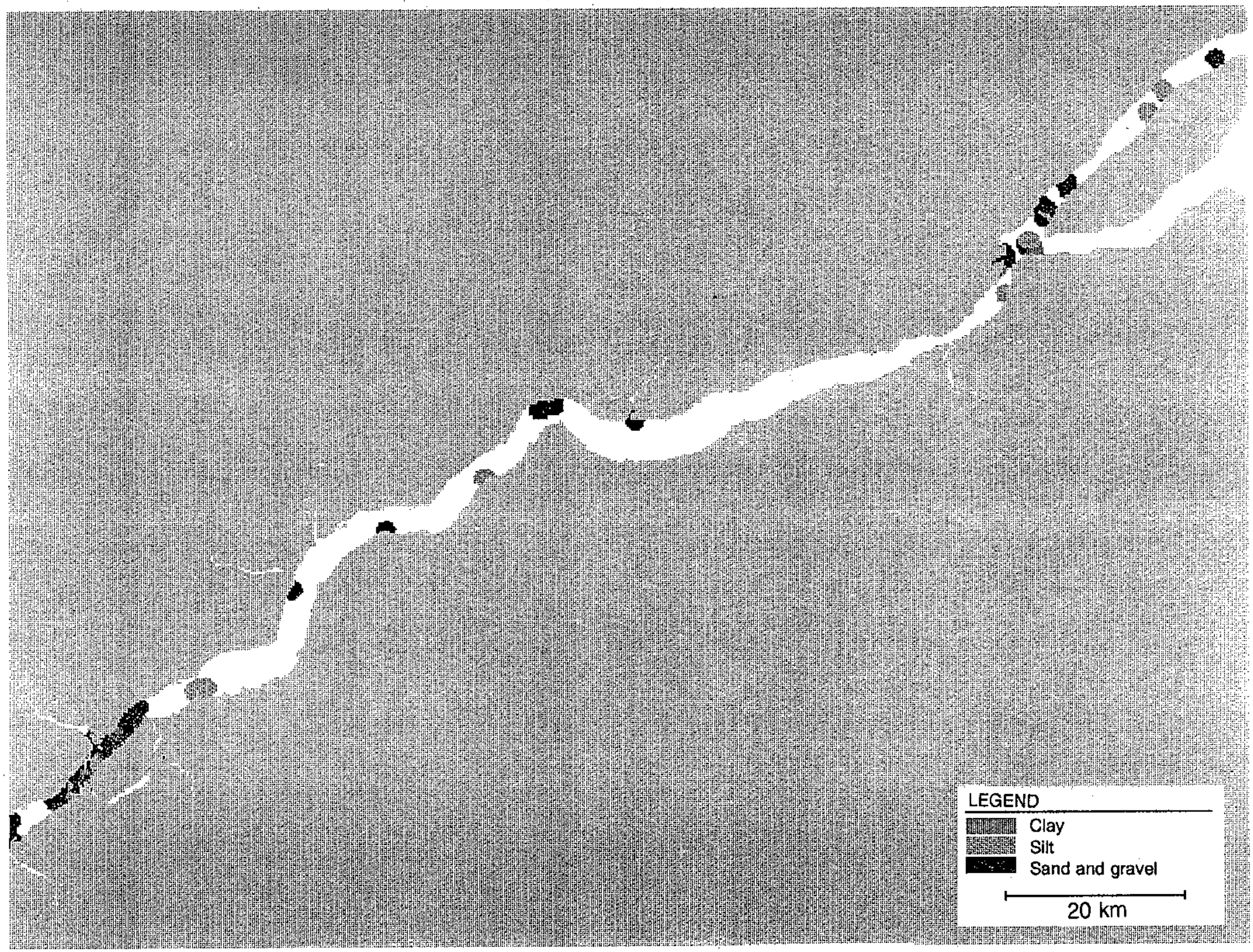


Figure 58 **Dominant size fractions in the riverine estuary**

Table 41 Dominant size fractions in the riverine estuary

Area	Size class	Number of stations	Mean %	Standard deviation	Minimum %	Maximum %
Mouth of the St. Maurice River	Clay	17	29	23	7	88
	Silt	17	20	19	1	84
	Sand	17	51	25	0	89
Bécancour	Clay	12	19	6	6	25
	Silt	1	74	6	56	80
	Sand	12	7	9	1	31
St. Charles River estuary	Clay	44	11	5	0	27
	Silt	44	30	22	0	67
	Sand	44	59	26	15	100
Lévis	Clay	34	19	2	0	29
	Silt	34	48	5	1	64
	Sand	34	35	27	5	99
Lauzon	Clay	28	22	14	0	47
	Silt	28	42	18	1	66
	Sand	28	36	30	5	99
Channel north of Île d'Orléans	Clay	18	20	17	2	57
	Silt	18	39	21	0	59
	Sand	18	41	33	1	9
Total for the riverine estuary	Clay	406	21	15	0	98
	Silt	406	31	25	0	84
	Sand	406	48	30	2	100

studied. The surveys did nevertheless show major local contamination by two of the six metals studied, zinc and chromium. The main contaminated areas are the docks and fine-sediment deposition zones in contact with waters of the St. Maurice River.

Median concentrations of mercury (0.08 μg/g) (Table 42) indicate that mercury levels in the riverine estuary are generally low, slightly above background level. Highest mercury levels were recorded at a few stations at the mouth of the St. Charles and Portneuf rivers and in the north channel (tables 43 and 44; figures 59 and 60); median concentrations at these stations were moderate. Elsewhere in the subsystem mercury concentrations were very low.

Copper levels were also very low in 1976 (median of 21.7 μg/g), around background level. Copper levels were high only at a few stations at the mouths of the Portneuf and St. Charles rivers (Figure 61).

Measured zinc levels were also generally background levels (median of 102 μg/g). The most contaminated area was the mouth of the St. Charles River where a maximum 5370 μg/g was detected. Moderate contamination was detected at stations in the mouth of the Portneuf River, around the Bécancour dock and in the north channel (Figure 62).

Serious lead contamination was detected at only a few St. Charles River stations in 1976 (maximum of 670 μg/g). On the whole, lead concentrations measured in the riverine estuary were background levels (median of 12 μg/g) (Figure 63).

Measured cadmium concentrations suggest generalized cadmium contamination of the entire subsystem (median of 5 μg/g). All parts of the subsystem were cadmium contaminated, without exception. The most contaminated area was the mouth of the St. Charles River (maximum of 35 μg/g) (Figure 64).

Table 42 Riverine estuary sediment quality statistics

Year	Metal	No. of samples	% samples below detection level	Mean (µg/g)	Standard deviation (µg/g)	Median (µg/g)	Minimum (µg/g)	Maximum (µg/g)
1976*	Pb	82	0	19.79	10.04	12.00	0.00	670.00
	Cd	82	0	5.71	2.01	5.00	1.00	35.00
	Zn	82	0	174.13	51.47	102.00	25.60	5 370.00
	Hg	82	6	0.14	0.14	0.08	0.01	0.77
	Ni	82	0	25.66	13.48	23.40	6.10	107.00
	Cu	82	0	31.35	28.48	21.70	4.50	302.00
	Cr	82	0	61.07	18.88	55.70	24.20	258.00
1985-1988**	Pb	27	0	83.70	128.03	58.00	1.90	680.00
	Cd	22	0	0.69	0.67	0.07	0.00	2.10
	Zn	27	41	294.51	367.76	193.00	18.00	1 360.00
	Hg	27	0	0.16	0.19	0.09	0.01	0.66
	Ni***	-	-	-	-	-	-	-
	Cu	27	0	43.30	36.24	36.00	1.00	140.00
	Cr	22	0	29.72	30.21	18.90	3.00	116.00

* Sérodes (1978)
** Studies for dredging projects in the St. Charles estuary and at Bécancour, Portneuf and St. François de l'Île d'Orléans
*** Insufficient data

Chromium concentrations, like those of most other metals in the subsystem, were background levels (median of 55.7 µg/g). The mouth of the St. Charles River was highly contaminated by chromium in spots. Contamination was moderate in the Bécancour area and in the north channel (Figure 65).

Nickel concentrations were also, on the whole, background levels (median of 23.4 µg/g). Nickel levels were high at only one station, at the mouth of the St. Charles River. Moderate contamination was detected at a few Bécancour and north channel stations (Figure 66).

On the whole, contamination levels were low in the riverine estuary in 1976, generally lower than in reaches upstream. The only exception was cadmium; cadmium contamination was general throughout the subsystem. Though the mouth of the St.

Table 43 Median concentrations (µg/g) in four riverine estuary areas

Year	Metal	Bécancour	Portneuf	St. Charles River	North channel
		Median	Median	Median	Median
1976	Pb	14.00	15.00	25.00*	22.00*
	Cd	6.00	5.00	3.00*	7.00*
	Zn	114.00	111.00	398.00*	194.00*
	Hg	0.11	0.02	0.02*	0.42*
	Ni	37.10	10.80	15.10*	36.80*
	Cu	31.80	26.60	44.80*	34.80*
	Cr	70.80	30.70	33.70*	83.50*
1985-1988	Pb	2.00*	--	101.00	42.00
	Cd	0.00*	--	0.50	1.43
	Zn	29.00*	--	250.00	145.00
	Hg	0.05*	--	0.09	0.13
	Ni	--	--	--	54.00
	Cu	5.40*	--	61.00	25.00
	Cr	6.50*	--	22.90	82.00

* Value computed from very few measurements (1 to 3)
-- No data available

Charles River was not extensively sampled in 1976, disturbing signs of contamination were noted.

Since the riverine estuary was not sampled as exhaustively as the river proper in the 1980s, its quality in this decade could not be assessed in as much detail. The only data available for the period between 1985 and 1988 are from environmental assessments for dredging projects in harbours and in parts of the seaway channel conducive to sedimentation. The mouth of the St. Charles River was sampled more extensively in the 1980s than in the 1976 survey. Though sediment of the Québec City harbour was characterized between 1989 and 1991 for development of a harbour restoration plan, the results are not directly considered herein because the analyses performed and the substrata examined differed from those considered in this report. The harbour studies did nonetheless indicate major contamination--mainly by copper, zinc, cadmium and PCBs--of the St. Charles estuary and Louise Basin (Procéan, 1990, 1991a, 1991b, 1992a and 1992b).

Table 44 Maximum metal concentrations (µg/g) in four riverine estuary areas

Year	Metal	Bécancour	Portneuf	St. Charles River	North channel
		MAXIMUM	MAXIMUM	MAXIMUM	MAXIMUM
1976	Pb	29.00	19.00	670.00*	22.00*
	Cd	9.00	8.00	35.00*	7.00*
	Zn	196.00	158.00	5 370.00*	194.00*
	Hg	0.17	0.34	0.75*	0.42*
	Ni	59.40	33.30	107.00*	36.80*
	Cu	55.80	169.00	302.00*	34.80*
	Cr	96.40	80.30	258.00*	83.50*
1985-1988	Pb	2.00*	--	680.00	58.00
	Cd	0.00*	--	1.00	2.17
	Zn	30.00*	--	1 360.00	198.00
	Hg	0.06*	--	0.66	0.16
	Ni	--	--	--	70.00
	Cu	5.40*	--	140.00	38.00
	Cr	7.50*	--	43.60	116.00

* Value computed from very few measurements (1 to 3)
-- No data available

Median concentrations of mercury during the two periods are similar (0.08 µg/g in 1976 and 0.09 µg/g in 1985-1988); this is a low level of contamination. Mercury levels were lower in the north channel (dredged annually because of heavy sedimentation) in 1988 than in 1976, suggesting suspended sediment which has settled there recently is of better quality than sediment deposited in the 1970s. The riverine estuary is slightly less

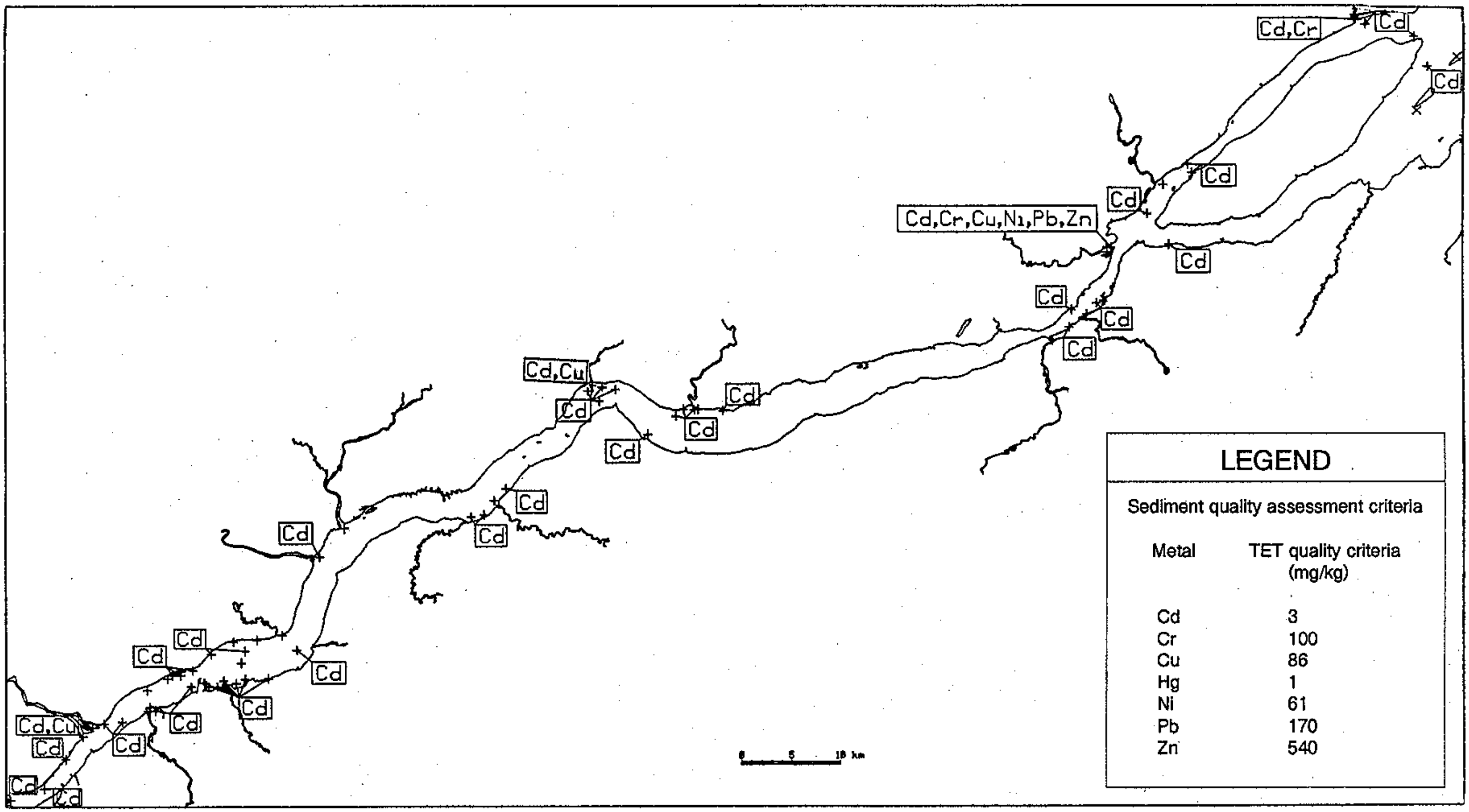


Figure 59 Exceedences of TET quality criteria in riverine estuary sediment (1976)

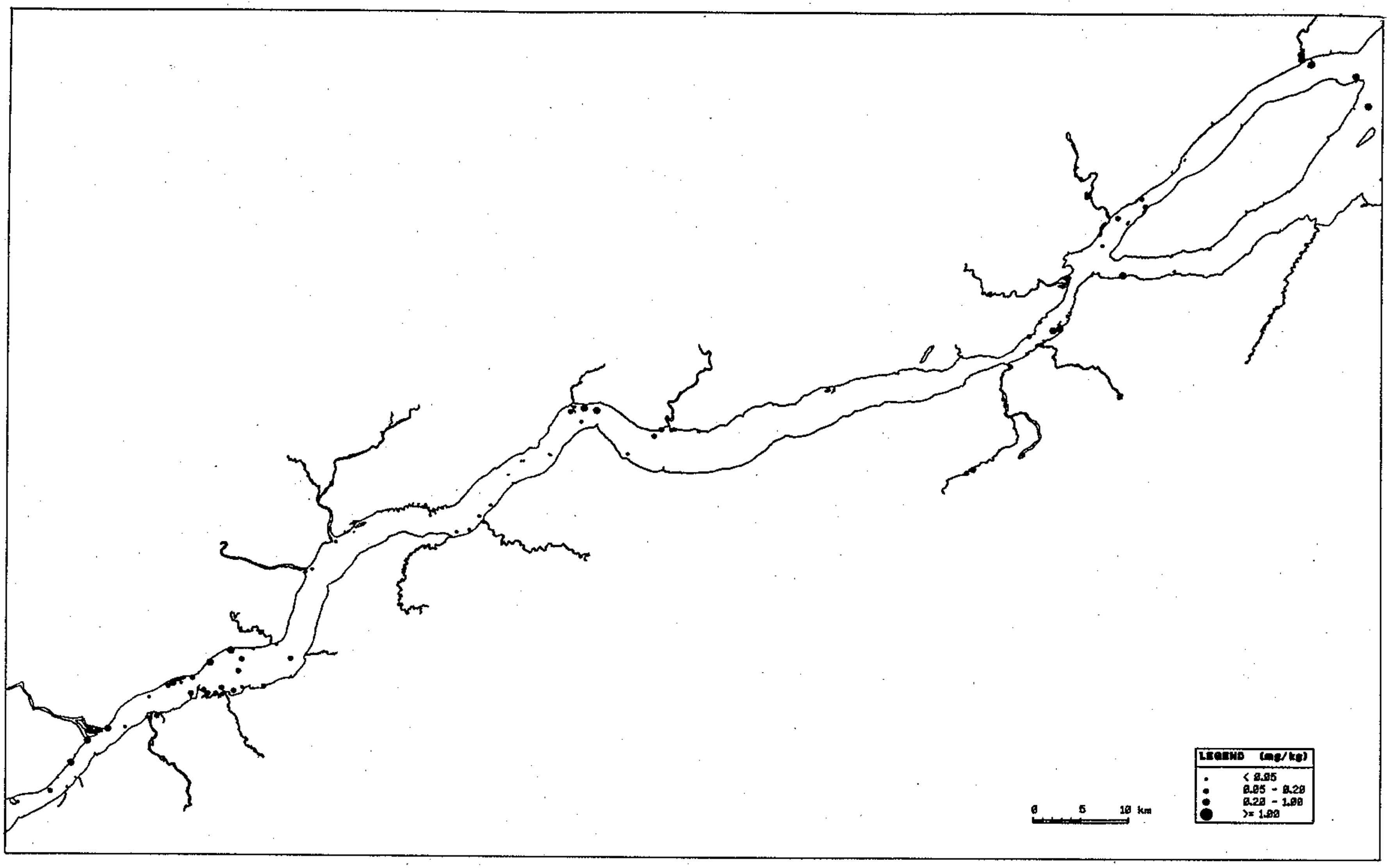


Figure 60 ***Mercury distribution in riverine estuary sediment (1976)***

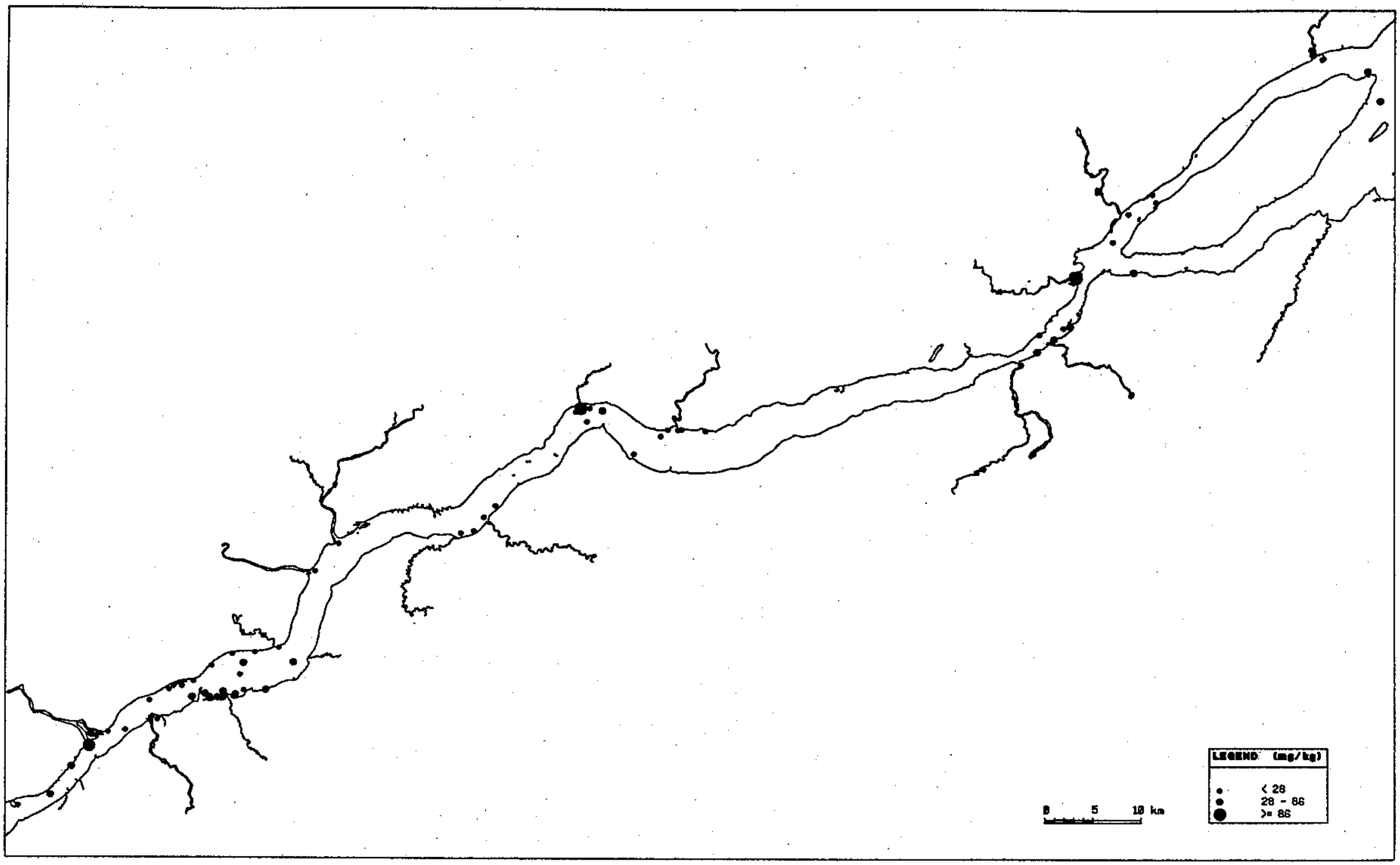


Figure 61 Copper distribution in riverine estuary sediment (1976)

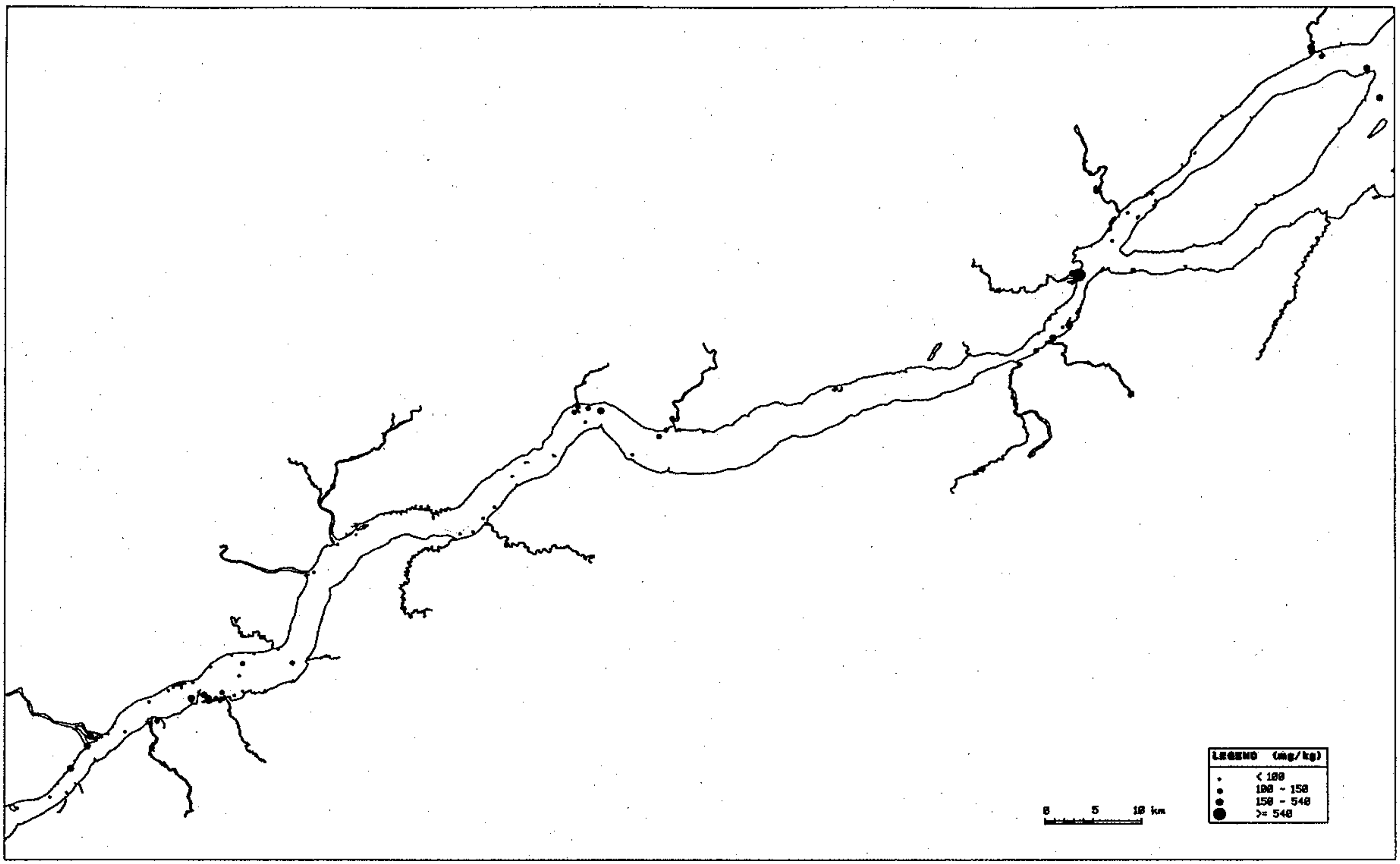


Figure 62 Zinc distribution in riverine estuary sediment (1976)

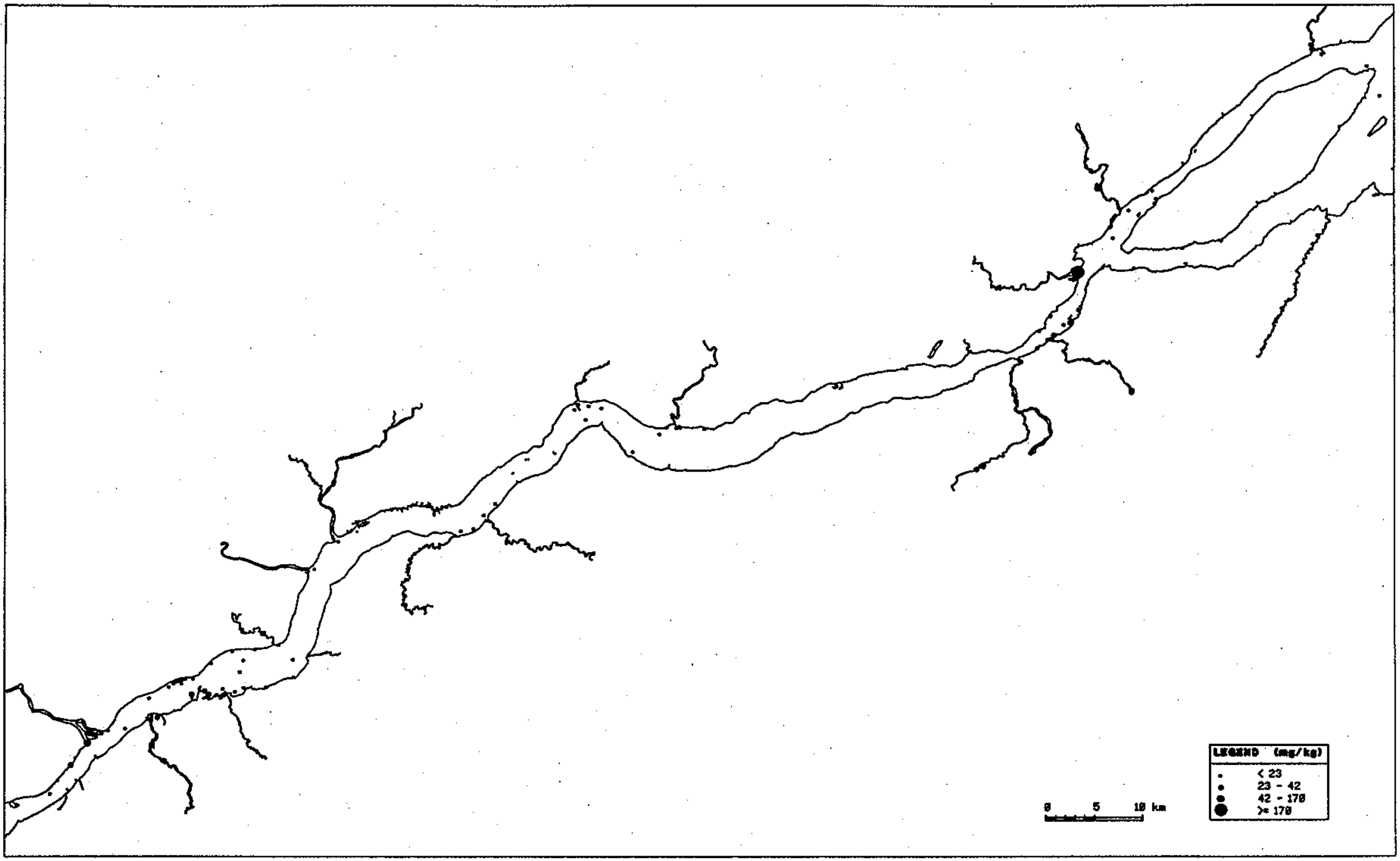


Figure 63 Lead distribution in riverine estuary sediment (1976)

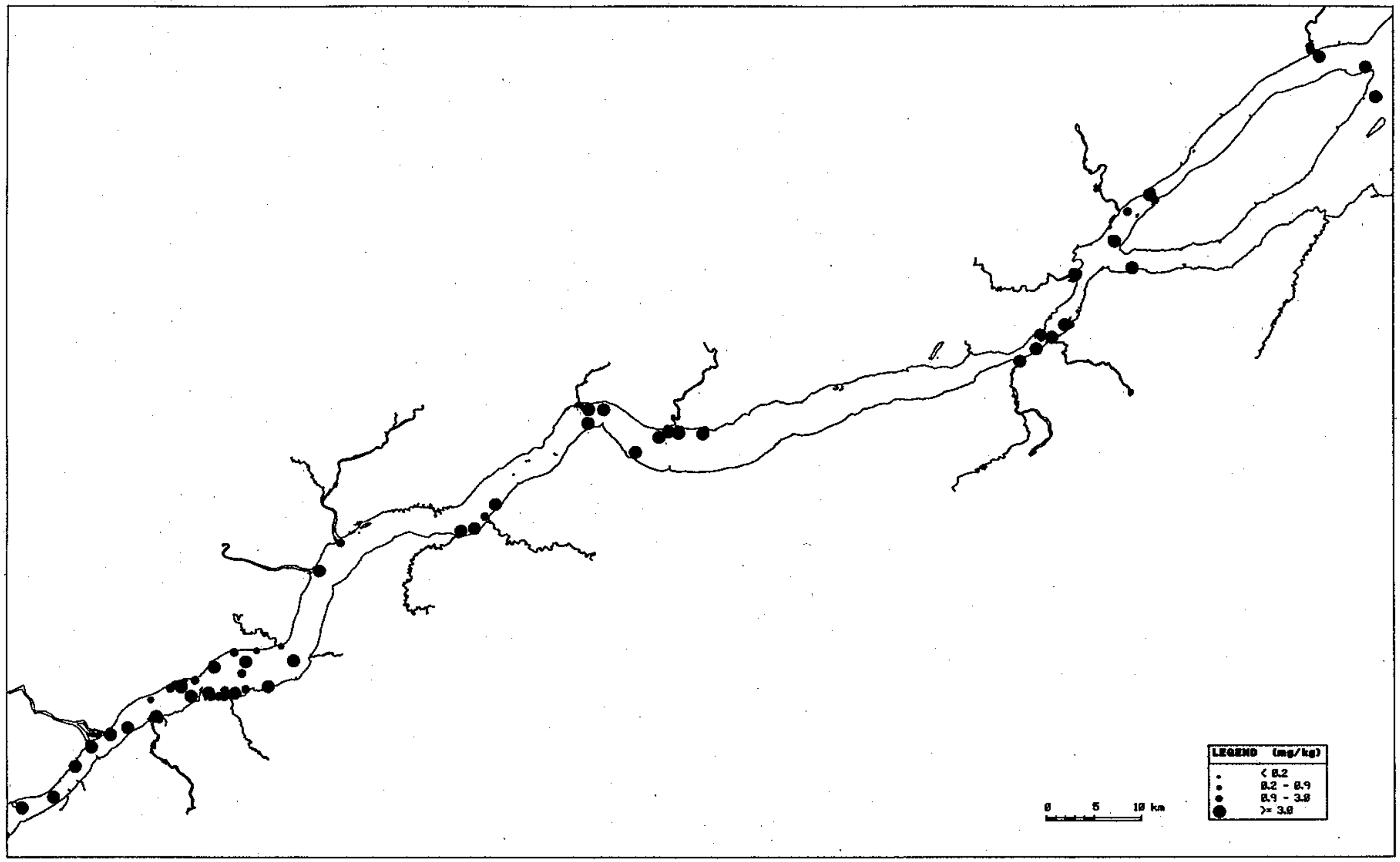


Figure 64 ***Cadmium distribution in riverine estuary sediment (1976)***

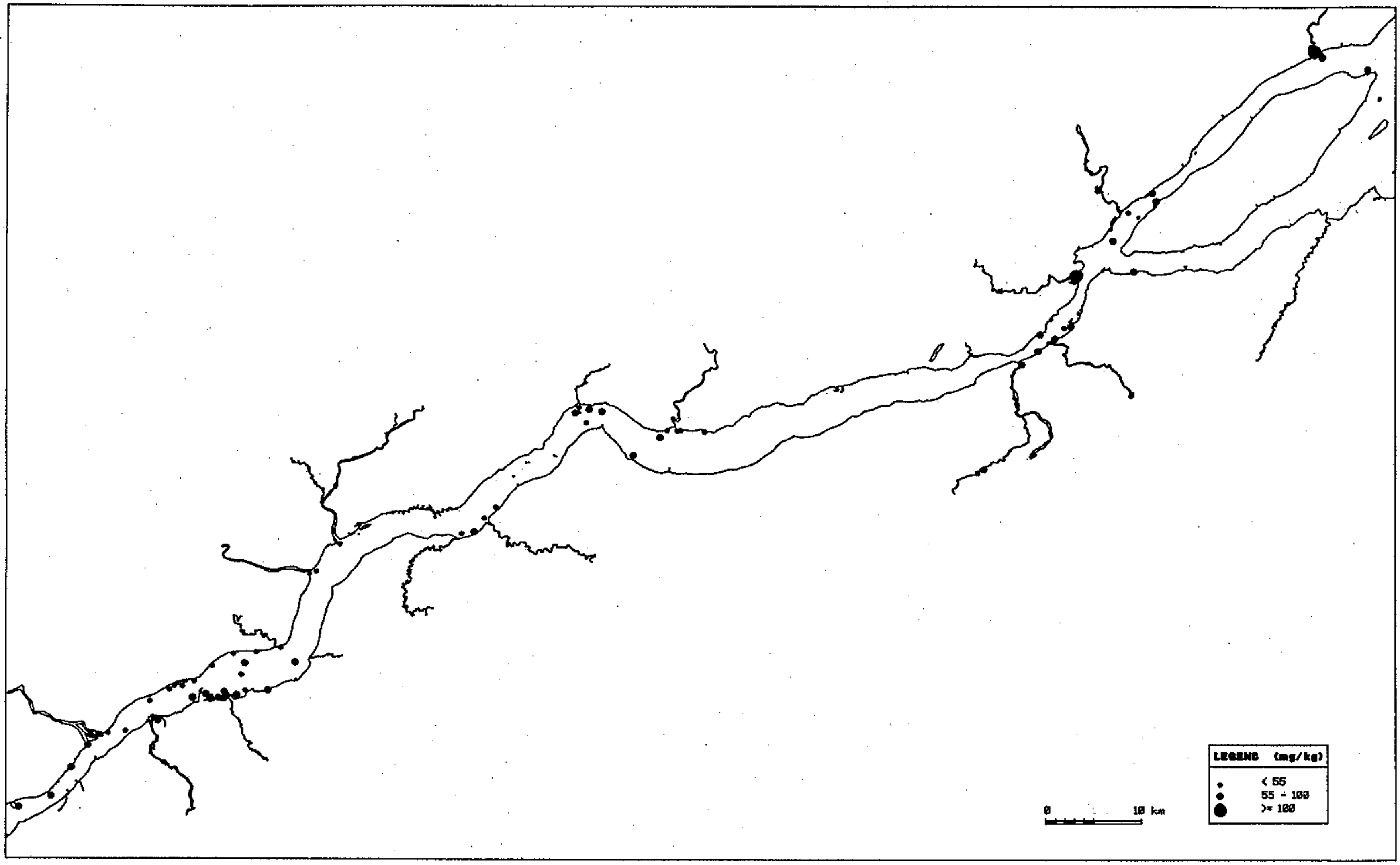


Figure 65 Chromium distribution in riverine estuary sediment (1976)

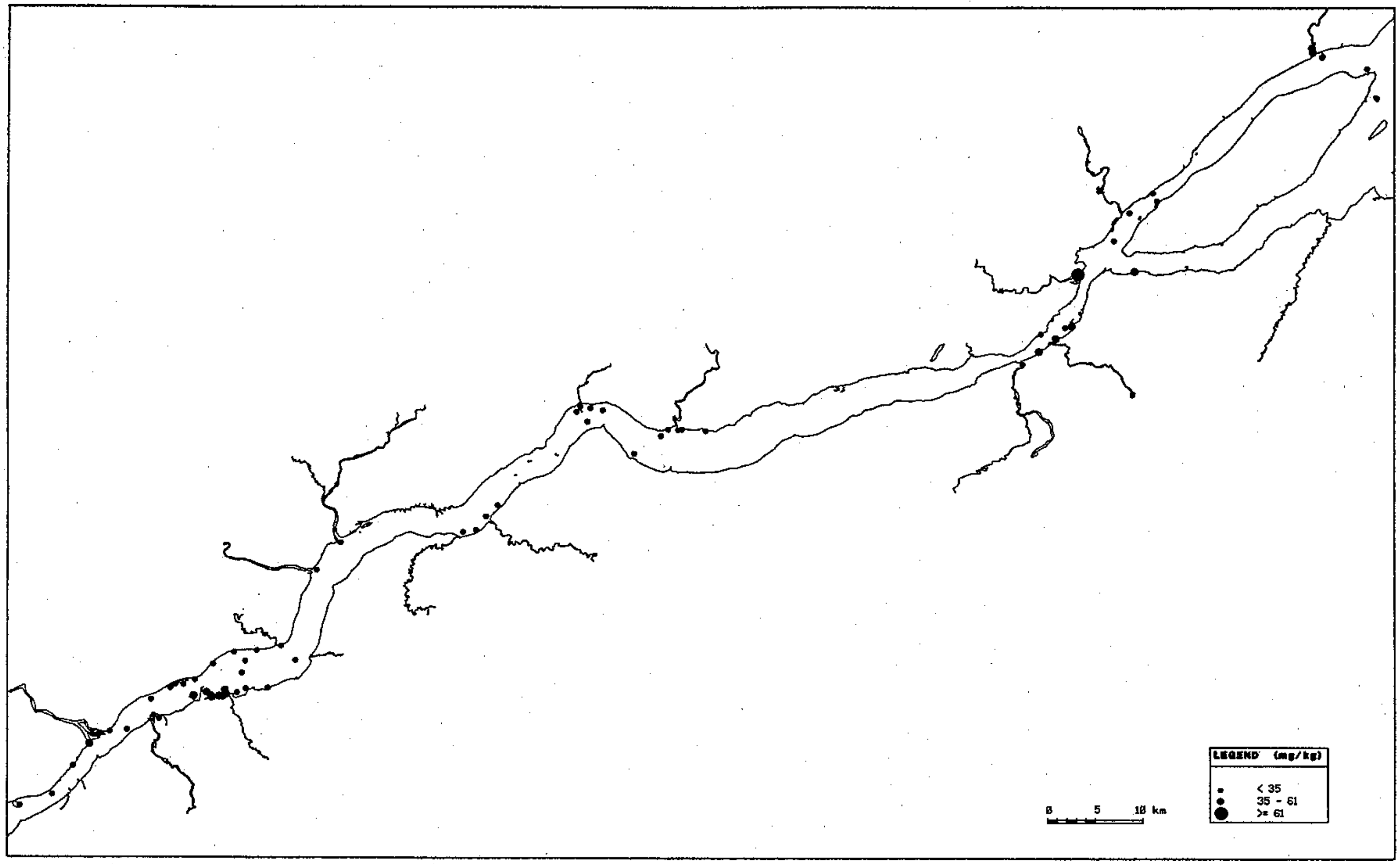


Figure 66 ***Nickel distribution in riverine estuary sediment (1976)***

contaminated by mercury than the river proper. The mouths of the St. Maurice and St. Charles rivers are moderately contaminated by mercury (Figure 67).

The riverine estuary is not conducive to deposition of contaminants from upstream. In addition, there is less industrial activity here then around Montréal, and the major municipal discharges are to the downstream end of the subsystem and hence do not affect median concentrations much. Also, the complex currents associated with the tide in the downstream half of the riverine estuary cause substantial mixing of waters, and sediment spreads out over a greater area as a result, making contamination less perceptible.

On the whole, the riverine estuary was slightly more contaminated by copper in the 1980s than it was a decade earlier (median was 21.7 μg/g in 1976 and 36 μg/g in 1985-88). Copper concentrations varied greatly from one spot to the next however. The Bécancour bend and the north channel--both dredged frequently in the past--seem to have recovered slightly, but there was no significant change in copper contamination of the mouth of the St. Charles River (Figure 68). On the whole, copper contamination of the riverine estuary was low, comparable to that of Lake St. Louis (35 μg/g).

Asseau (1992d) identified two major sources of copper: the St. Maurice River (860 t/a), which contributes 86 percent of total tributary input; and upstream reaches of the St. Lawrence River (720 t/a). In comparison, municipal and industrial copper input (7 and 0.3 t/a, respectively) to the subsystem was negligible. Tributaries and upstream reaches of the St. Lawrence River are probably responsible for contamination of the subsystem's sediment deposition areas. Local sources, however, are probably responsible for contamination of the mouth of the St. Charles River (Procéan, 1990, 1991a, 1991b, 1992a and 1992b).

Zinc levels were higher in 1985-1989 than in 1976; median rose from 102 to 193 μg/g over the decade. These values, however, probably reflect better sampling of the mouth of the St. Charles River in 1985-1988 (where moderately high zinc levels were detected) rather than an increase in contamination of the subsystem as a whole.

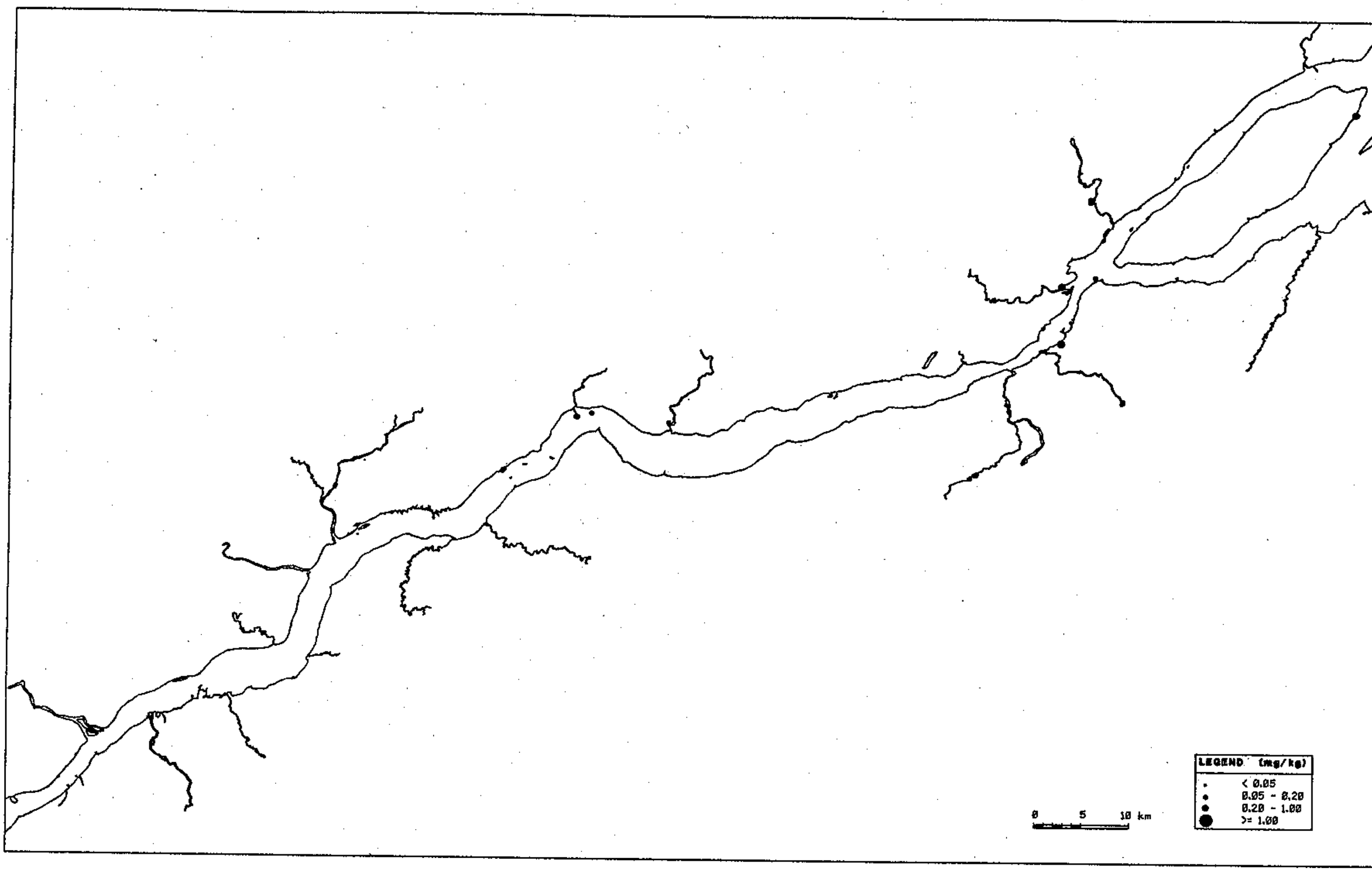


Figure 67 Mercury distribution in riverine estuary sediment (1985-1988)

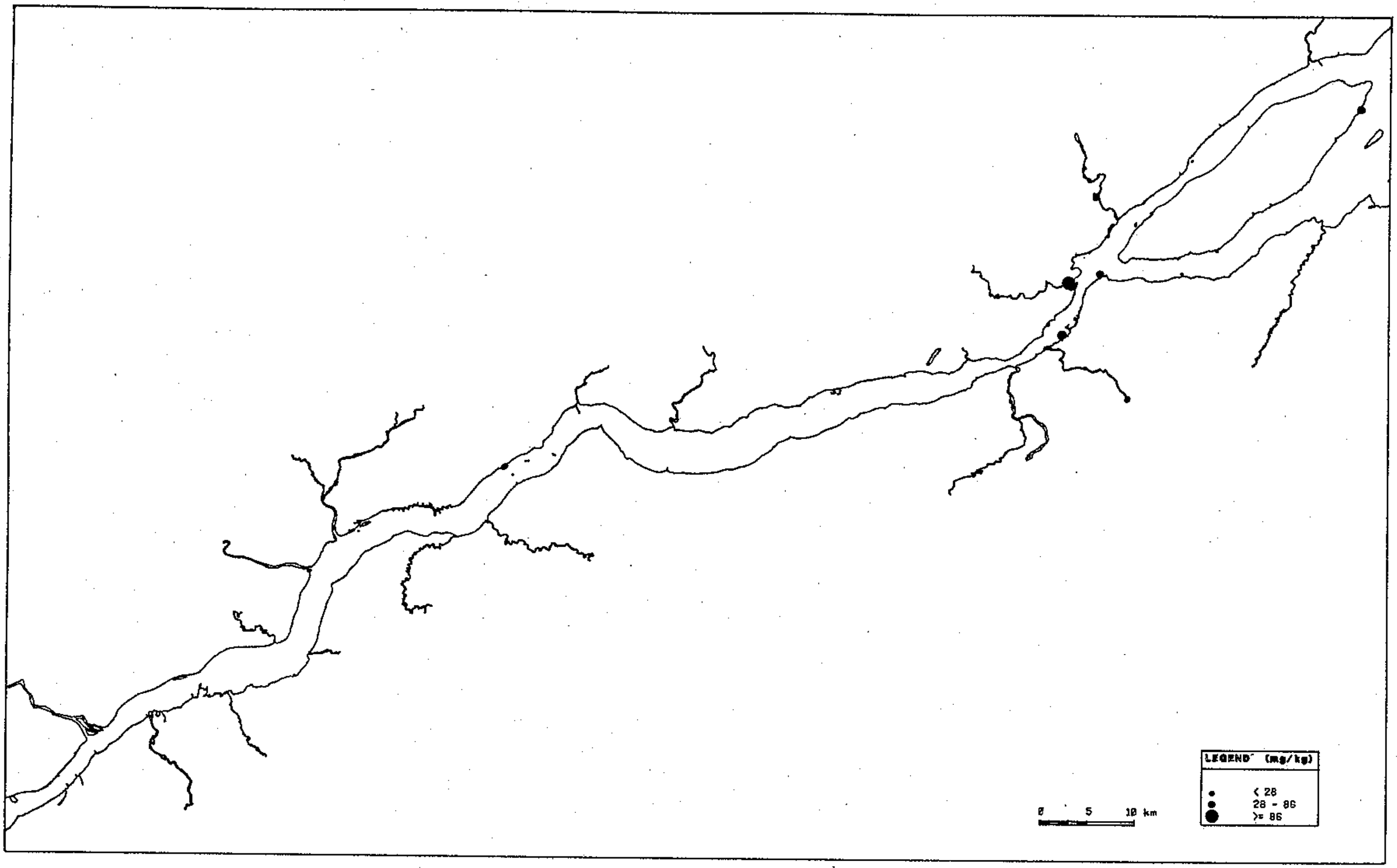


Figure 68 Copper distribution in riverine estuary sediment (1985-1988)

Specifically, between Pointe du Lac and Lévis zinc concentrations were rather low (Figure 69). Moderate contamination was detected at Lévis, at Lauzon, in the north channel and at the mouth of the St. Charles River. Zinc contamination of the mouth of the St. Charles River seems attributable to local sources, and that of Lévis and Lauzon nearshore to local industrial activities (Procéan, 1990). Contamination of the north channel may derive from local sources and from upstream reaches of the St. Lawrence River (the main source of zinc). Local input has been estimated as follows: tributaries, 890 t/a, including 7 t/a from the St. Charles River; municipalities, 27 t/a; and industrial discharges, 5 t/a. Input transported from upstream reaches of the St. Lawrence River has been estimated at 1626 t/a (Asseau, 1992d).

The riverine estuary appeared more lead-contaminated in 1985-1988 than a decade earlier; median concentration rose from 12 μg/g in 1976 to 58 μg/g in 1985-1988. As with zinc contamination, these values really reflect better sampling of the mouth of the St. Charles River in 1985-1988--an area moderately contaminated by lead (101 μg/g). Lead contamination between Pointe du Lac and Lévis, however, was low. High lead levels were detected in sediment from the Lévis marina, however, and moderate levels were detected in the north channel (Figure 70). The mouth of the St. Charles River was much more contaminated than the three riverine lakes upstream, suggesting the contamination comes from local sources (Procéan, 1990); lead contamination of the mouth of the St. Charles River was comparable to that of the lesser La Prairie basin (137 μg/g). Lead input was estimated as follows: tributaries, 620 t/a, including 5 t/a from the St. Charles River; upstream reaches of the St. Lawrence River, 295 t/a; municipalities, 13 t/a (Asseau, 1992d).

Cadmium contamination of the subsystem was low (median of 0.07 μg/g), an improvement over the preceding decade (median was 5 μg/g in 1976). Low to moderate contamination was detected at Deschambault, at Leclercville, in the mouths of the Jacques Cartier and St. Charles rivers and in the north channel (Figure 71). Cadmium comes to the subsystem from upstream reaches of the St. Lawrence River, tributaries and local sources (industrial plants, harbours, marinas and so forth).

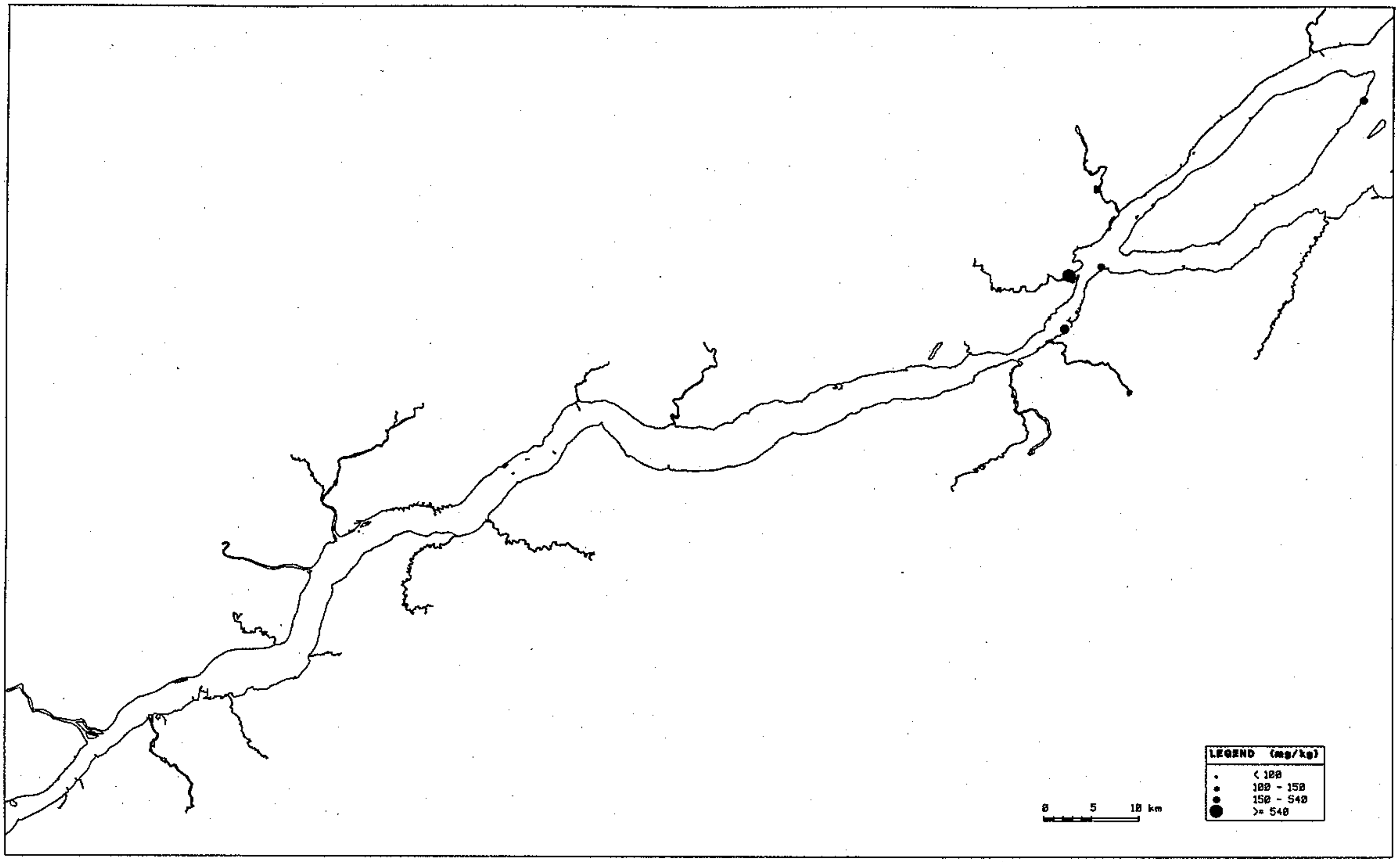


Figure 69 ***Zinc distribution in riverine estuary sediment (1985-1988)***

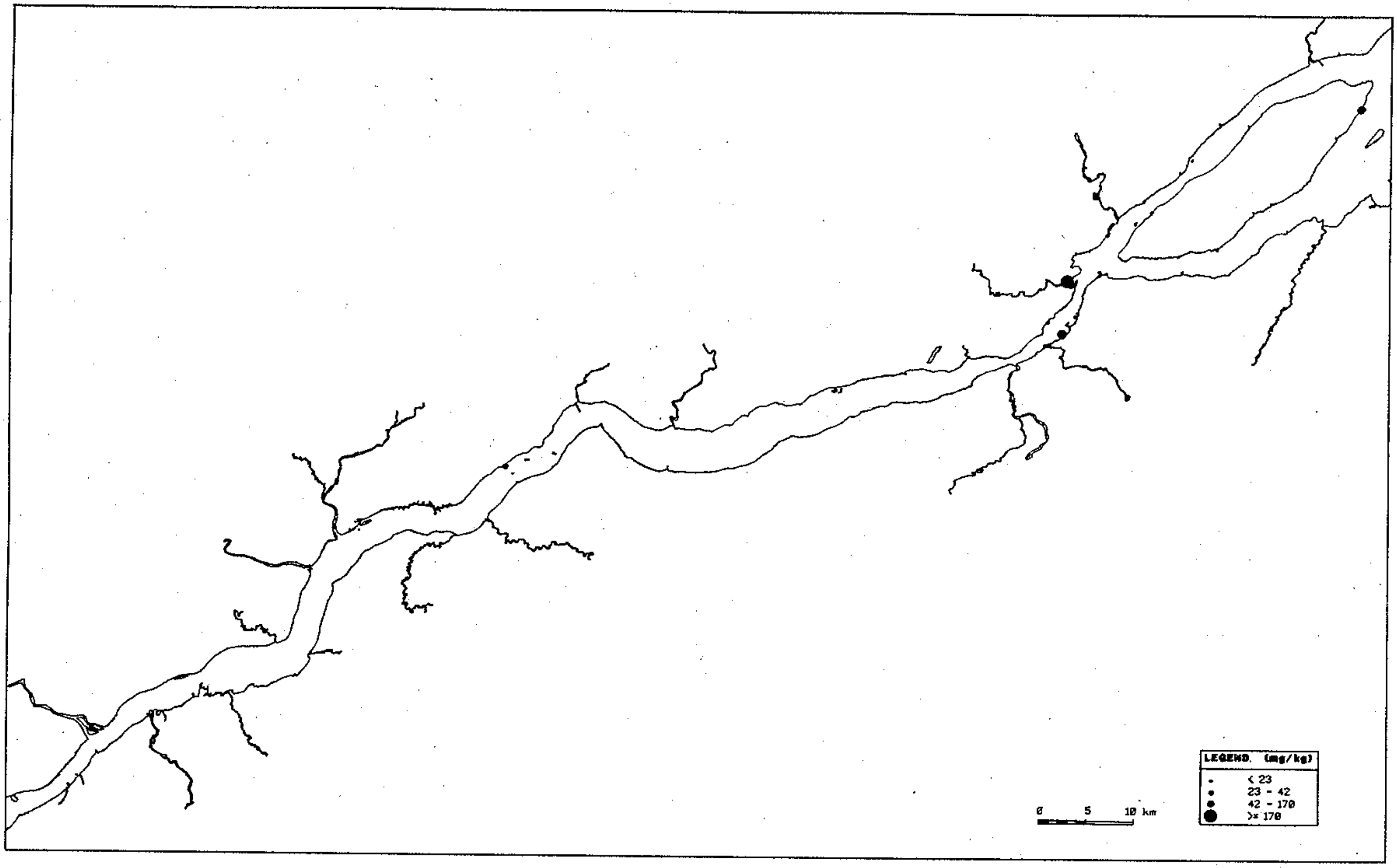


Figure 70 ***Lead distribution in riverine estuary sediment (1985-1988)***

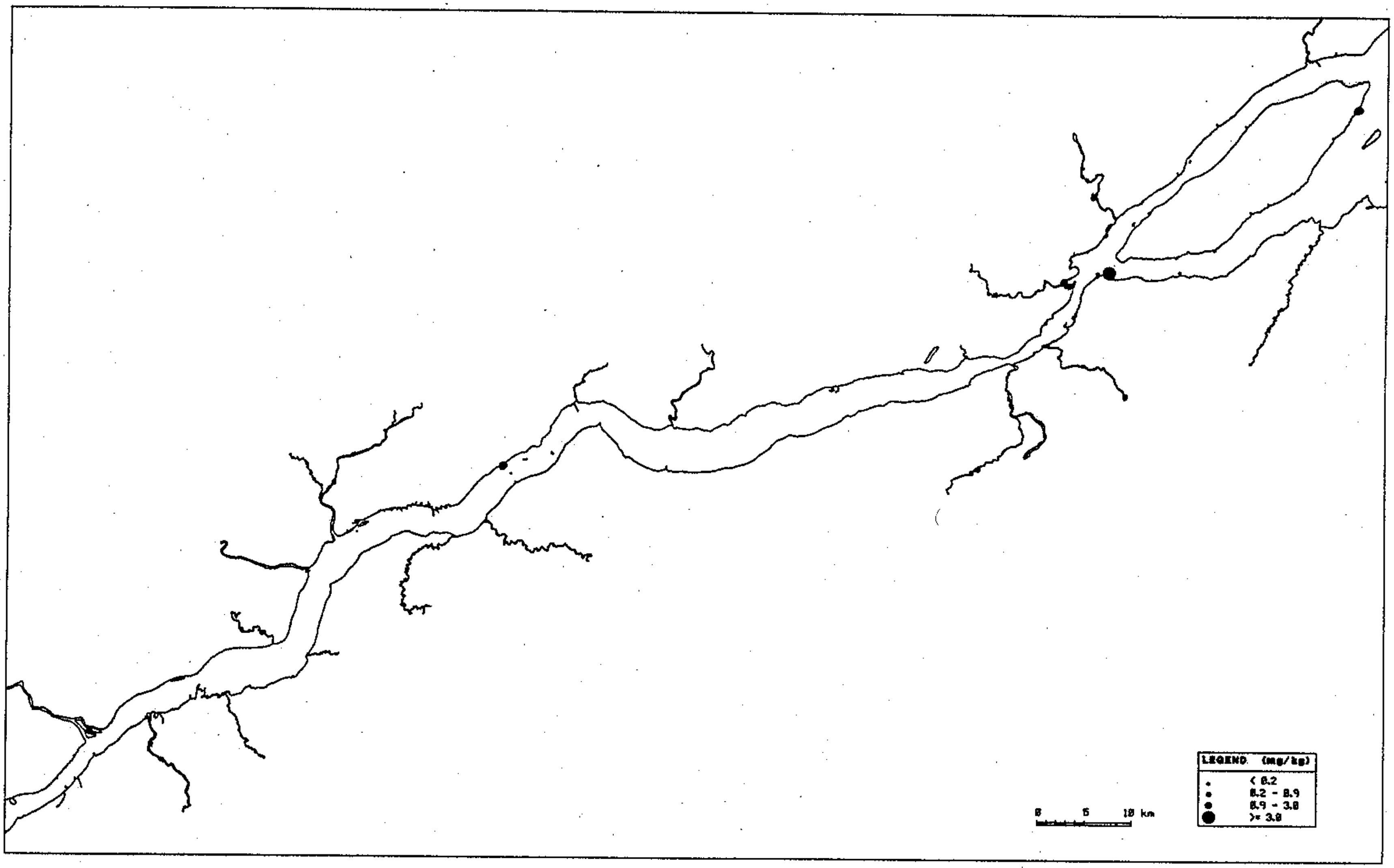


Figure 71 **Cadmium distribution in riverine estuary sediment (1985-1988)**

Subsystem chromium concentrations dropped over the decade (median was 55.7 μg/g in 1976 and 18.9 μg/g in 1985-88). Concentrations were background levels and lower than concentrations upstream (Figure 72). Highest chromium concentrations in 1985-1988 were in the north channel, where levels have not decreased since 1976. These findings are surprising given the drop in chromium concentrations noted elsewhere in the riverine estuary and the fact that the north channel was dredged frequently between 1976 and 1985-1988. Because only limited data on the riverine estuary are available for 1985-1988, the comparison between decades could not be as detailed for this subsystem as for subsystems upstream, particularly for the three lakes. In addition, nonuniform distribution of the sampling stations generated a systematic error in median values obtained for the riverine estuary, and this had to be taken into account when interpreting results. The mouth of the St. Charles river, which is highly contaminated, was well-represented in the samples, but there were insufficient data on the rest of the subsystem. As a result, trends noted in the riverine estuary must be considered less reliable than those detected in subsystems upstream.

The trends noted do nevertheless show an increase in copper, zinc and lead levels over the decade, a drop in cadmium and chromium concentrations, and stable mercury levels. Chromium excepted, trends were the same at the mouth of the St. Charles River (which has never been dredged) and in the channel north of Île d'Orléans (which is dredged annually).

As for spatial distribution of contaminants in the freshwater section of the river in general, levels of most metals (copper, zinc, lead, chromium and nickel) increase between Lake St. Francis and the lesser La Prairie basin (where they reach maximum values) and then decrease gradually downstream. Highest median concentrations of mercury were detected in Lake St. Louis, after which levels gradually decrease downstream, like those of the other contaminants. Spatial distribution of cadmium could not be determined because detection limit selected for certain characterization projects was too high (1.00 μ/g).

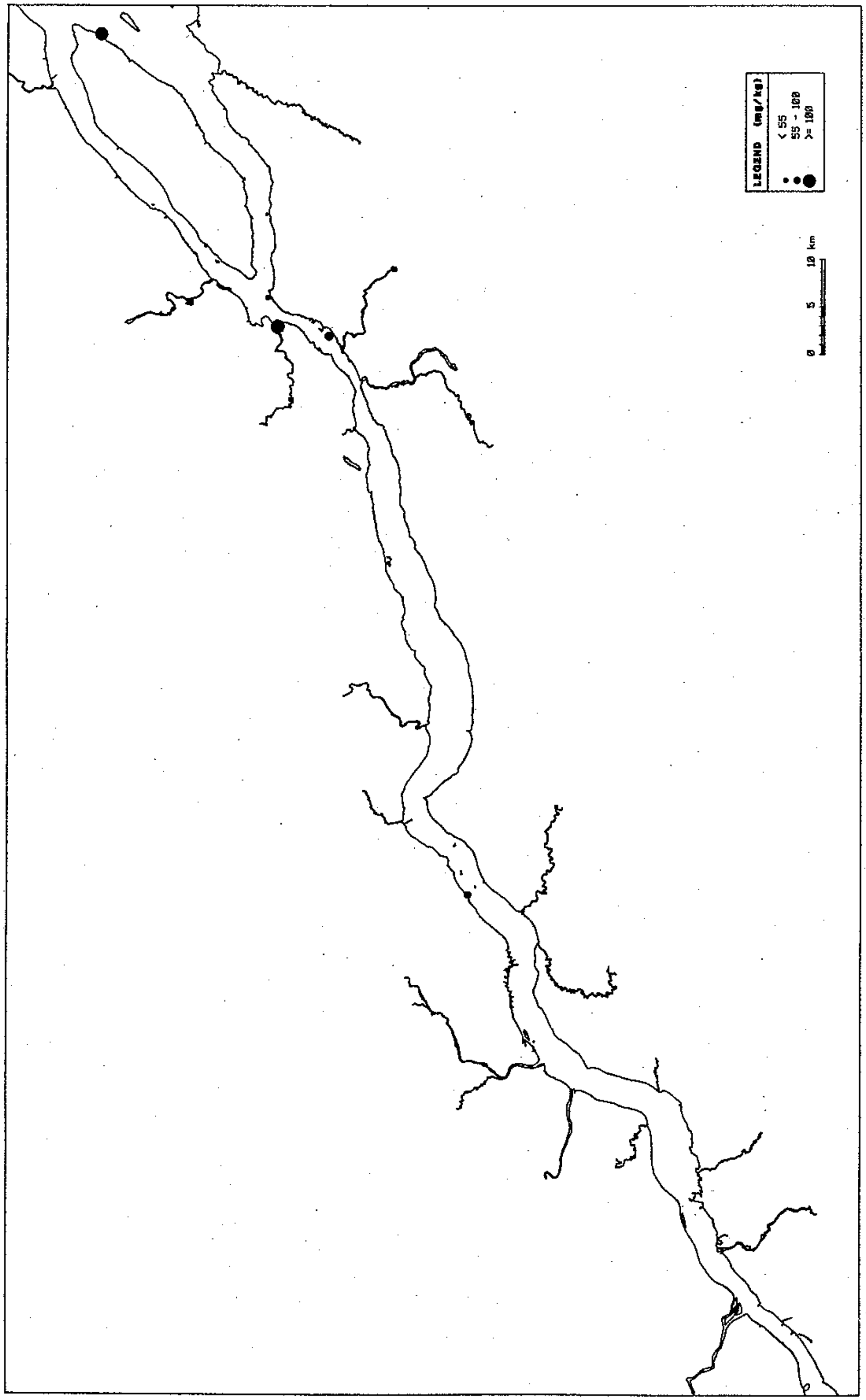


Figure 72 Chromium distribution in riverine estuary sediment (1985-1988)

6 SEDIMENT QUALITY IN THE UPPER ESTUARY

6.1 Subsystem 4: Île d'Orléans to Tadoussac (including the Saguenay)

6.1.1 Physiography and dynamics. The upper estuary of the St. Lawrence River begins at the east end of Île d'Orléans and ends at the mouth of the Saguenay Fjord. It is 150 km long and an average 17 km wide.

Bathymetry of this subsystem is relatively complex. There are three flow channels generally more than 10 m deep, one of which runs north-south between Île aux Coudres and the Isle aux Grues archipelago (Figure 73). A depression about 50 km long and sometimes more than 100 m deep begins around St. Siméon.

In general, the main channel runs along the north side of the upper estuary and the south side is relatively shallow. Between Île d'Orléans and Île aux Coudres, the water is never more than 20 m deep except in the channels that run along both shorelines. Beyond Île aux Coudres but still in the northern part of the estuary, there are two large basins 50 m or more deep in places. Here, the shallow nearshore on the south side harbours about fifty islets or islands (the Isle aux Grues archipelago, Île aux Coudres, the Kamouraska Islands, Île aux Lièvres and Île Verte) and vast coastal marshes, mainly around Montmagny, Rivière du Loup, Kamouraska and Île Verte. There are also, of course, the Cap Tourmente flats immediately downstream of Île d'Orléans, on the north side of the estuary.

The upper estuary divides into two quite distinct parts. The upstream part, between Île d'Orléans and Île aux Coudres, is a freshwater-saltwater mixing zone that starts out only a few kilometres wide and ends 20 km across. The downstream part, where waters are stratified (freshwater on the surface and saltwater below), is very much like the lower estuary. Because of its bathymetry, however, this part of the estuary is nonetheless really an extension of the upper estuary right up to the Saguenay, where depth plunges from 25 m to 365 m in the space of 15 km.

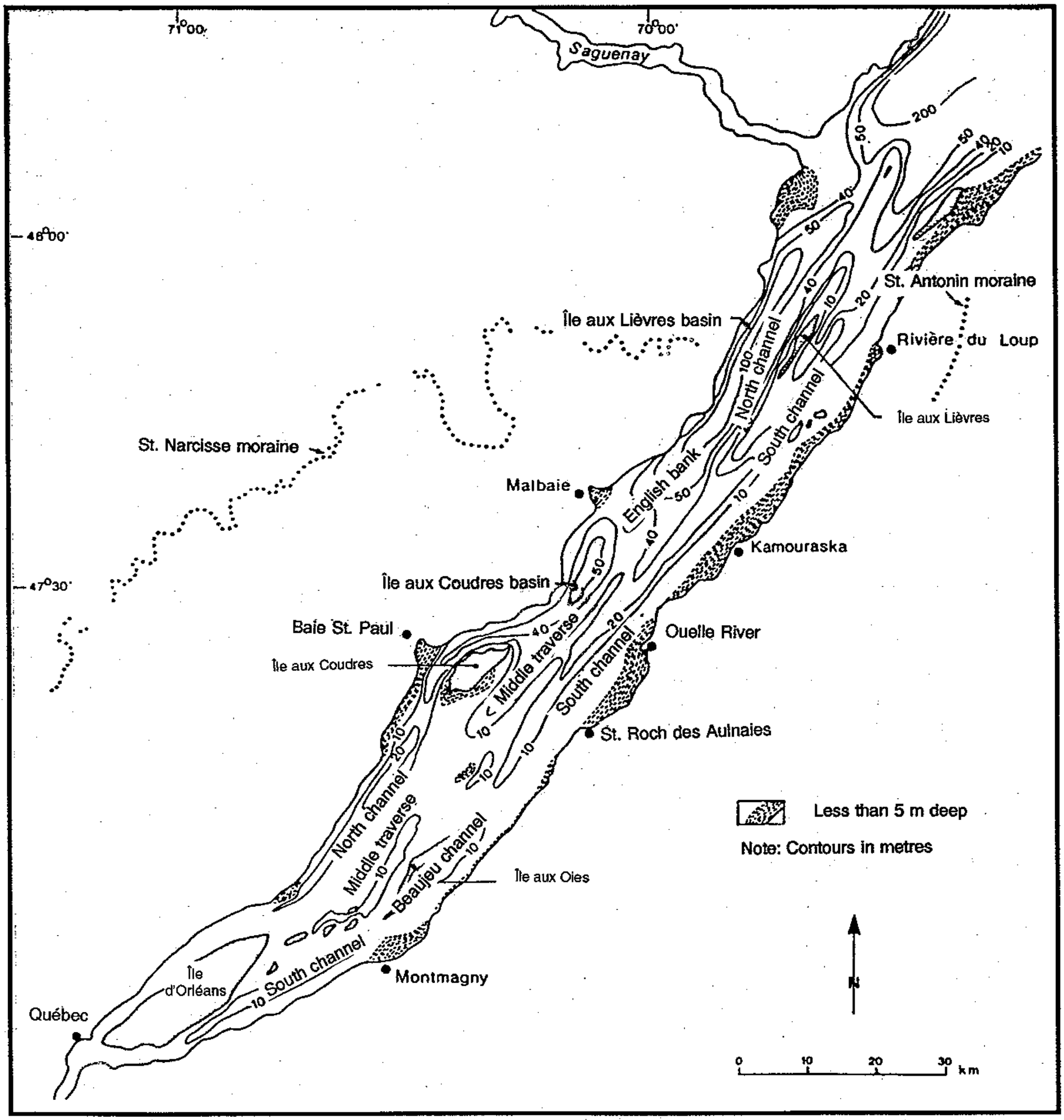


Figure 73 ***Bathymetry of the upper estuary of the St. Lawrence River (after Lavalin, 1985)***

General information on currents in the upper estuary of the St. Lawrence River is available, in particular data from a Canadian Hydrographic Service station offshore of Île aux Basques (48°10'56"N, 69°15'16"W), around Trois Pistoles, where the estuary is about 28 km wide. The current data (from recordings that span a full tidal cycle) show that for the first five hours of the tidal cycle currents are slow (less than 50 cm/s). The current runs north at first but turns northeast four hours after high tide and continues in this direction till the next high tide. Velocity hits 80 cm/s for two hours following low tide and then decreases gradually. Circulation dynamics offshore of Trois Pistoles are thus dominated by currents running downstream; currents run north for only four hours and they are slow.

A thermohalocline runs through most of the Saguenay from the mouth of the fjord to Ha! Ha! Bay, dividing the water column into two distinct layers: a thin surface layer of warm freshwater and a deep layer of cold saltwater. In fact, circulation dynamics of the fjord are entirely conditioned by intrusion of water from the St. Lawrence estuary into the deep basins of the fjord with the tide.

Flow velocities near the mouth of the Saguenay are about 2.0 m/s, and can reach 3.0 to 3.6 m/s at the sill that divides the fjord into two basins (Schafer et al., 1990). About 20 km west of Tadoussac, tide currents are virtually imperceptible. At Chicoutimi, surface currents range from 1.0 et 1.5 m/s and generally run downstream except for a short period at the end of the rising tide when current direction reverses.

The upper layer of the "inner" or western basin of the Saguenay tends to be freshwater from the Saguenay, especially in spring and early summer. The waters remain highly stratified until late fall. During winter, stratification diminishes gradually, till it is reestablished by the spring flood. In the "outer" or eastern basin, the waters are more mixed because of the vigorous stirring action of the ebb and flow of the tides.

In general, currents in the Saguenay tend to form eddies conducive to deposition of fine material in bays and areas away from the main channel. Around St. Fulgence, there is a large intertidal marsh.

Flow dynamics in the St. Lawrence estuary and the Saguenay are affected by the tide cycle. Because the estuary grows narrower and shallower towards Québec City, tide range increases upstream. In the upper estuary, water levels rise in response to the tides faster than they fall.

Mean diurnal tide-generated fluctuations in water level are about 3.5 m in the St. Lawrence and about 4.0 m in the Saguenay. Table 45 shows tide ranges at St. François (Île d'Orléans), Trois Pistoles, Tadoussac, La Baie and Chicoutimi estimated from tide tables of the Canadian Hydrographic Service.

Highest tides anywhere in the St. Lawrence estuary are at the eastern tip of Île d'Orléans.

Tidal range increases substantially as the semidurnal tidal wave propagates into the Saguenay estuary from Tadoussac to La Baie, where maximum range is 6.8 m at spring tide (equivalent to tidal range at the eastern tip of Île d'Orléans). Tidal ranges are slightly lower at Chicoutimi (6.3 m at spring tide) (Fisheries and Oceans Canada, 1992).

Saltwater intrudes to downstream of Île d'Orléans, with preferential flow along the north shore. Salinity increases from 10 to 27 parts per thousand between Île aux Coudres and the Saguenay.

Wave climate in the upper estuary is basically controlled by the orientation of the St. Lawrence River. Only winds blowing along the longitudinal axis of the estuary, that is, northeast and southwest, can blow for hundreds of kilometres and generate big waves.

As is well known, wave conditions are quite unusual at the mouth of the Saguenay because of upwelling of deep waters from the Laurentian Trough and the encounter of these waters with freshwater from the St. Lawrence and the Saguenay. The phenomenon is further complicated by winds and tide. The standing wave that characterizes this area can easily reach a height of 2 to 3 m; wave period is short. Upstream in the Saguenay, wave conditions are generally fluvial.

Table 45 Tidal elevations in the upper estuary (m)

	St. François Île d'Orléans	Trois-Pistoles	Tadoussac	La Baie	Chicoutimi
Mean high-water, spring tide	5.5	4.1	4.3	5.0	4.6
High high-water, spring tide	6.6	5.1	5.4	6.3	6.1
Mean low-water, neap tide	0.9	0.8	0.7	0.7	0.8
High low-water, neap tide	-0.2	0.0	-0.1	-0.5	0.0
Mean water level	3.0	2.3	2.4	2.8	2.4
Mean tidal range	4.6	3.3	3.6	4.3	3.8
High tidal range	6.8	5.1	5.5	6.8	6.3

Ice begins to form in the upper estuary between early and mid-December depending on the weather. The March spring tides generally clear the nearshore of ice. Ice also forms on the Saguenay in December. The Canadian Coast Guard maintains a shipping channel throughout the winter and speeds the departure of the ice near the end of March.

The meeting of freshwater and saltwater, the turbulent action of waves and wind, the widening basin and the drop in current speeds together turn the head of the upper estuary into a high turbidity zone where concentrations of suspended particulate matter (SPM) increase dramatically. Whereas SPM concentrations are 10 et 20 mg/L at Québec City and about 2 mg/L at the Saguenay, downstream of the eastern tip of Île d'Orléans they range from 200 to 400 mg/L (Frenette and Verrette, 1976). These high concentrations are the source of an unusual deposition/erosion cycle: between June and September, a layer of fine material as much as 10 to 30 cm thick accumulates on protected flats where vast intertidal marshes develop. When the marsh vegetation disappears, erosion occurs and fine material is flushed into the water column by fall storms and spring tides (Troude et al., 1983). Net deposition rate on the flats is negligible and mean residence time of the particles is about one year (D'Anglejan, 1990). The core of the maximum turbidity zone is in the north channel of the estuary, in front of the intertidal flats and marshes of Cap Tourmente.

It has been demonstrated that seasonal fluctuations in intensity and position of this core are mainly determined by suspended sediment exchanges between the channel and the marshes. Hence fine sediment found between Cap Tourmente and Île aux Coudres in winter and early spring is advected over the flats during the summer months by the tide. Favoured by marsh plant growth, deposition can reach 500 000 t in three months. A period of intense erosion (about 4500 t per tide) coincides with destruction of the plant cover in the fall. The material removed fills up the Île d'Orléans channel upstream and is flushed back downstream during the next spring flood (Lucotte and D'Anglejan, 1986).

6.1.2 Sources of contamination. According to Malo (1978), toxic input from upstream reaches of the St. Lawrence River (estimated at Québec City) constitutes more than 80 percent of toxic contributions to the upper and lower estuaries. Tributaries, mainly those along the north shore, come next; they contribute 10 percent of toxic input to the estuary. Industrial discharges and to a lesser extent municipal discharges supply the rest of the toxic input.

Apart from toxic input from upstream reaches of the St. Lawrence River (the main source of contamination of the estuary as a whole), there are a few point sources in the upper estuary that may have a very local impact on sediment quality (Lavalin Environnement, 1989).

Main potential sources on the north shore are as follows: the Donohue plant at Clermont (heavy metals and organics), which discharges wastewater to the Malbaie River after primary treatment in a reactor-clarifier; municipal discharges to the Malbaie River from La Malbaie and Pointe au Pic (heavy metals and hydrocarbons); and harbour facilities and marinas at St. Joseph de la Rive, Pointe au Pic, St. Siméon, Port au Persil and Tadoussac (hydrocarbons)

Contaminant sources on the south shore include industrial discharges from F.F. Soucy in Rivière du Loup after primary settling (heavy metals and organics), municipal discharges from Montmagny and Rivière du Loup (heavy metals and hydrocarbons) and harbour activities in Rivière du Loup and Cacouna (hydrocarbons). Tributaries that drain vast farming areas (Rivière du Sud and Ouelle River) may also contribute significantly to sediment contamination in the upper estuary (metals and organics).

Among potential sources of contamination of the Saguenay are the Alcan facilities in La Baie, Jonquière, Laterrière and Alma, the mill operated by Stone Consolidated in La Baie, the facilities of Cascades Inc. in Jonquière, the Price Ltd. facilities in Kénogami and Alma, and the Services TMG facilities in St. Honoré. Effluents as well as waste and residue storage activities of these pulp and paper, metallurgy and mining facilities release conventional contaminants, heavy metals and organics that may contaminate the Saguenay River and the lower estuary. Municipal discharges from Jonquière, Chicoutimi, Alma and La Baie are also potential sources of contamination (metals and hydrocarbons) as are harbour activities at Chicoutimi, Grande Anse and La Baie (metals and hydrocarbons).

6.1.3 Particle-size distribution. Sediment input to the estuary under the existing transport regime of the St. Lawrence River forms only minor deposits in the upper estuary covering no more than 10% of the floor (D'Anglejan, 1990). As Figure 74 shows, the upper estuary floor is occupied mainly by pelites (muds)--silty clays in which the clay fraction is 20 to 30% and the fine-to-very-fine sand fraction is 5 to 70%.

Intertidal salt marshes are found along both shores of the upper estuary. Between Grondines and Baie St. Paul, rush marshes dominate, covering close to 51 km^2. The largest concentration of marshes is in the area that includes the Cap Tourmente and Montmagny flats, the channel north of Île d'Orléans and the Isle aux Grues archipelago (Environment Canada, 1991b). In this area, the intertidal zones are large and gently

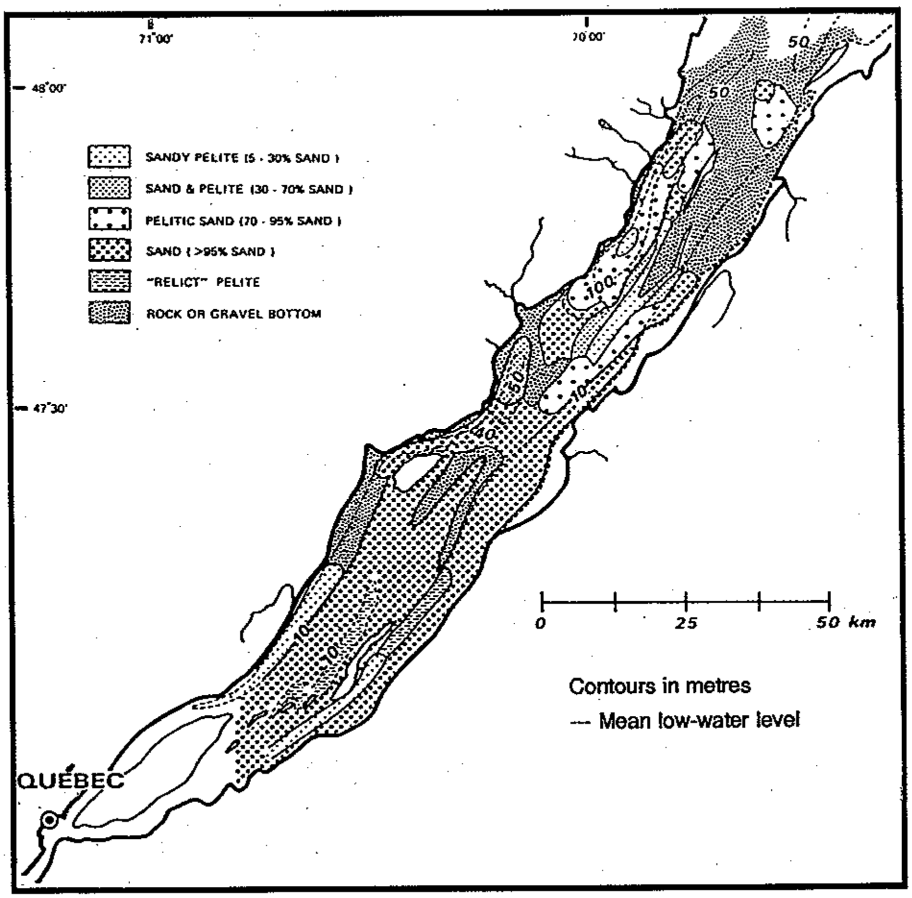


Figure 74 ***Distribution of recent sediment in the upper estuary (after d'Anglejan and Brisebois, 1978)***

sloping, the middle section covered by marsh vegetation dominated by American bulrush and the rest bare mudflats.

Protected basins in St. Lawrence River harbours are often deposition sites for fine sediment or, more rarely, sand. The deep basins of the Saguenay fjord downstream of Ha! Ha! Bay are major sites for deposition and accumulation of fine material.

Data from Dragsed, the data bank on dredging and sediment quality in the St. Lawrence River, was used to draft Figure 75. The figure shows dominant size fraction at each station sampled. The data are very site-specific and cannot be generalized for the upper estuary as a whole but they do confirm the variability of estuary floor and nearshore material.

6.1.4 Physical chemistry. Loring (1978a, 1979) and Loring et al. (1978, 1983) describe the distribution of certain trace metals in recent sediment in the St. Lawrence estuary, the Gulf of St. Lawrence and the Saguenay Fjord. Highest concentrations of chromium, copper, nickel, lead and zinc were detected in the pelites or muds of the upper estuary. Concentrations decrease seaward as natural and anthropogenic supply of suspended particulate matter diminishes.

The upper estuary acts as a sink for these elements: most of the trace metals introduced come from the riverine estuary and are adsorbed onto suspended fine material in the maximum turbidity zone and then transferred to the bottom in response to depositional conditions. Little suspended particulate material escapes seaward. Maximum deposition sites are a shallow depression (10 m) along the north side of the upper estuary 15 to 20 km below the head of the upper estuary and a deeper depression (up to 160 m) about 30 km seaward. Concentrations considered high for this environment (Cu > 30 μg/g, Pb > 20 μg/g and Zn > 100 μg/g) but low compared to those in the Montréal area were detected in these deposition areas. Highest concentrations of the three metals (202 to 348 μg/g of Zinc, 41 to 83 μg/g of Cu, 63 to 154 μg/g of Pb) were detected in the fine fraction of sediment at the head of the estuary and lowest concentrations were detected 65 km seaward. Relatively low percentages of these

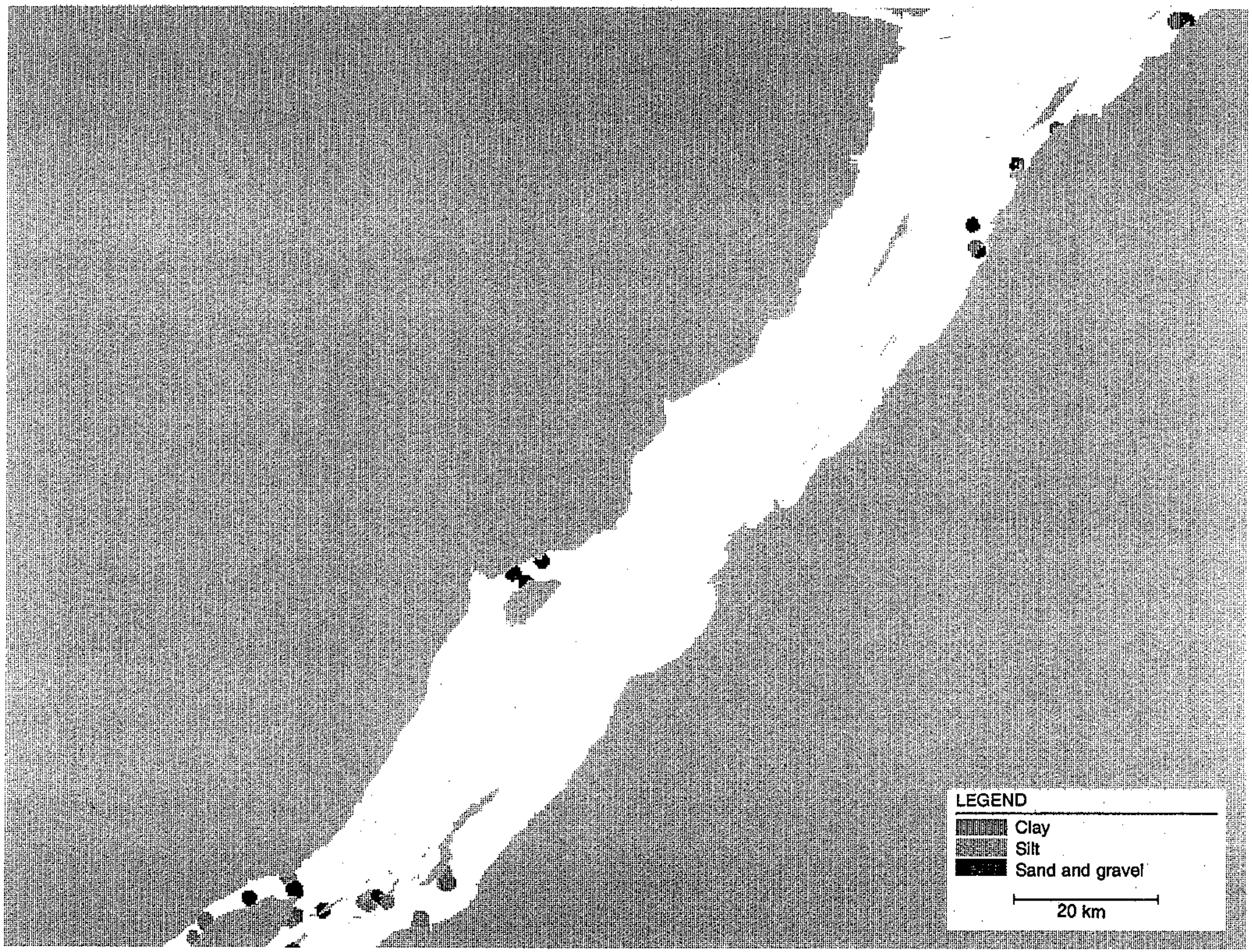


Figure 75 ***Dominant size fractions in the upper estuary***

metals (2 to 11 percent of chromium, 7 to 20 percent of copper, 12 to 23 percent of nickel, 15 to 26 percent of lead and 8 to 39 percent of zinc) are potentially bioavailable.

Table 46 lists mean metal concentrations in the upper estuary and the Saguenay Fjord. In the upper estuary, nickel concentrations are background levels, chromium, copper and lead concentrations show slight contamination, and zinc concentrations show moderate contamination. In the Saguenay Fjord, copper and nickel concentrations are background levels, chromium and zinc concentrations indicate slight enrichment, and lead concentrations show moderate enrichment.

Table 46 ***Mean metal (Cr, Cu, Ni, Pb and Zn) concentrations (µg/g) and standard deviations in pelites of the upper estuary and the Saguenay Fjord (Loring 1978a, 1979)***

Location	Cr	Cu	Ni	Pb	Zn
Upper estuary	92 ± 3.1	36 ± 8.5	27 ± 1.5	34 ± 4.5	185 ± 32
Saguenay Fjord	83 ± 10	27 ± 2.5	28 ± 4.6	47 ± 12.2	131 ± 32

Gobeil et al. (1989) noted lead concentrations increase from deep sediment to just below surface sediment in the Laurentian Trough and attributed the increase to growing use of lead over the last century. Lead constitutes more than 60 percent of anthropogenic contaminants transported by air over large distances (Dolske et al., 1979). Two thirds of the lead in recent sediment is anthropogenic. Gobeil et al. also noted a drop in surface sediment lead content and concluded that anthropogenic lead input has decreased over the last decade with greater use of unleaded gasoline.

Nearshore sediment was of good or passable quality in most upper estuary harbour areas and outfalls sampled for dredging projects. Contamination (chromium and nickel) was detected only at Montmagny, Île aux Grues and Rivière du Loup (Table 47); the main sources of contamination were municipal and industrial discharges, harbour facilities and marinas. Figures 76 to 83 give some indication of spatial distribution of contaminants covered by Dragsed.

Table 47 Extremes recorded in upper estuary nearshore sediment

Site	Year	Metal	TET criterion (µg/g)	Concen-tration (µg/g)
Isle aux Grues	1988	Cr Ni	100 61	140 83
Montmagny	1987	Cr	100	110
Rivière du Loup	1988	Cr Ni	100 61	118 62

Serious contamination by anthropogenic mercury discharged by a chlorakali plant was detected in surface sediment of the Saguenay Fjord; between 1940 and 1962, mercury level rose from 0.1 to 14.1 µg/g; that is, in 1962 it was forty times natural background (Barbeau et al., 1981). With abatement measures to reduce industrial discharges, mercury content of surface sediment in the inner basin of the fjord dropped sharply from 4.0 µg/g in 1969 to 0.4 µg/g in 1971. Between 1964 and 1976, an estimated 105 000 kg of mercury accumulated in sediment of the fjord (Loring et al., 1983) and about 120 000 kg (Loring 1978b) accumulated in the Saguenay system as a whole; most of the mercury (70 to 90 percent) was trapped by organic matter.

Mercury levels were especially high in the upper part of the fjord, where effluent from the chloralkali plant discharged between 1947 and 1976. Further downstream, the outer basin acted as a complementary sink, but it was less affected by the industrial discharges. Nowhere else in the upper estuary or the Gulf of St. Lawrence were such high mercury levels detected.

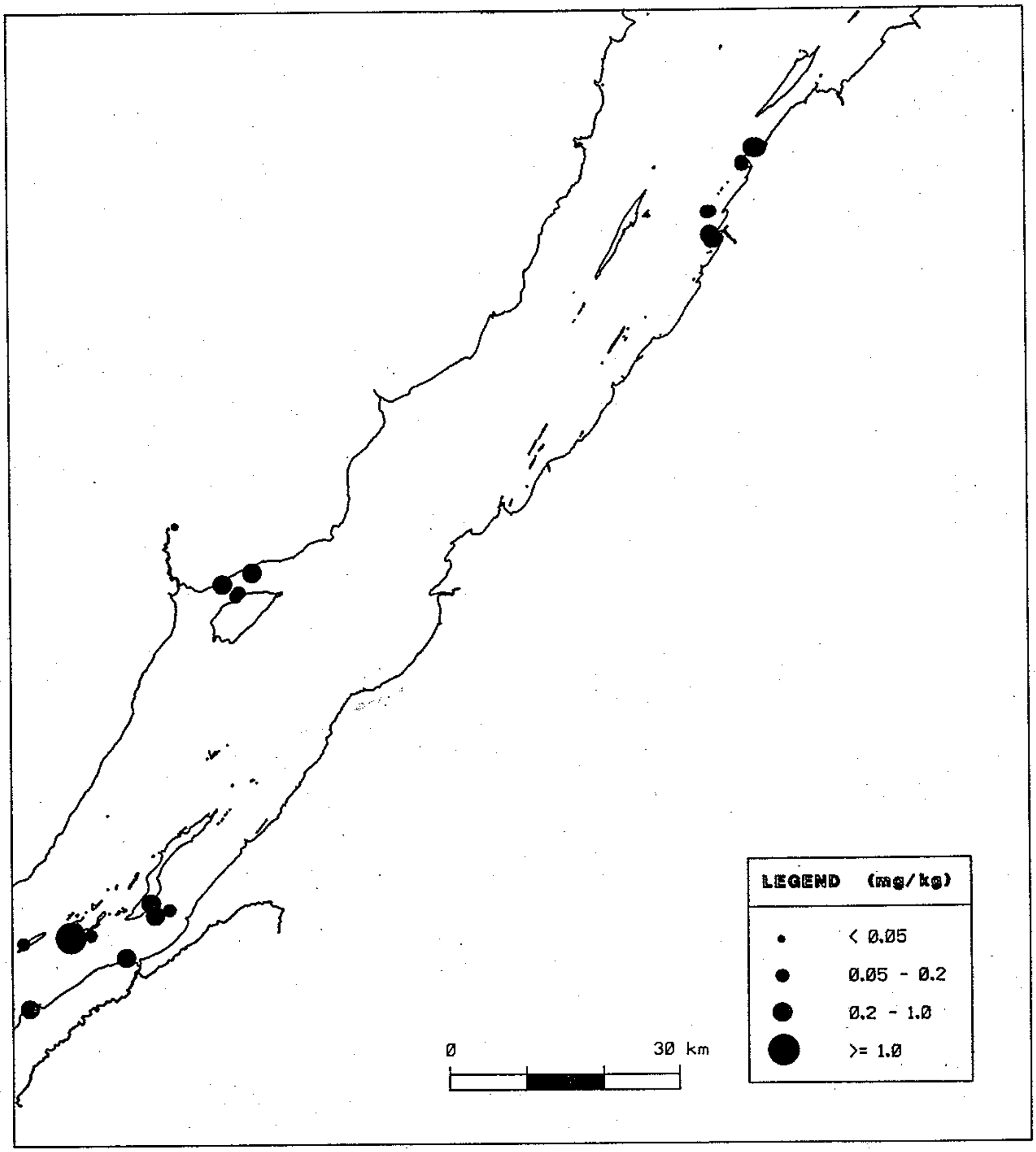


Figure 76 Mercury distribution in upper estuary sediment (1985-1991)

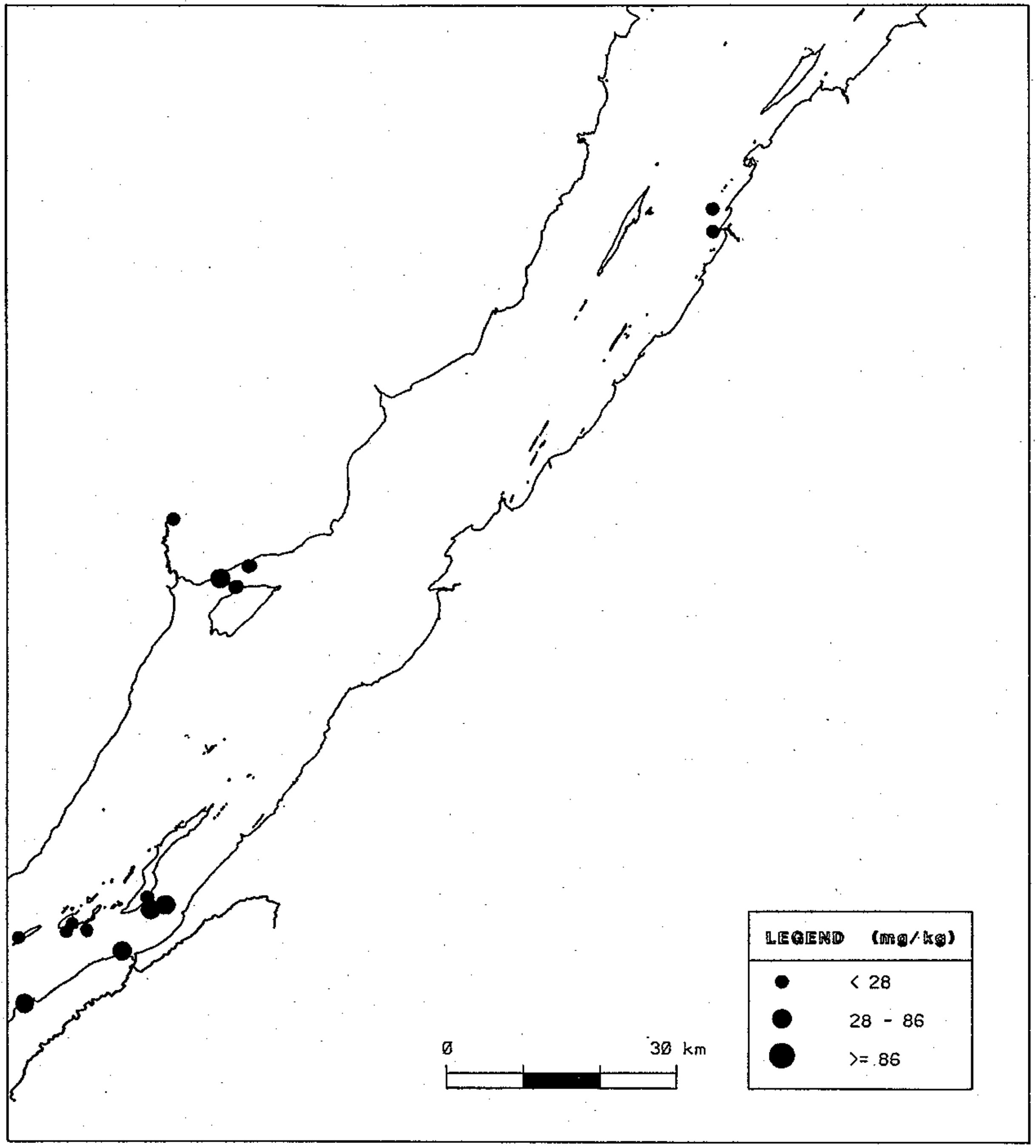


Figure 77 Copper distribution in upper estuary sediment (1985-1991)

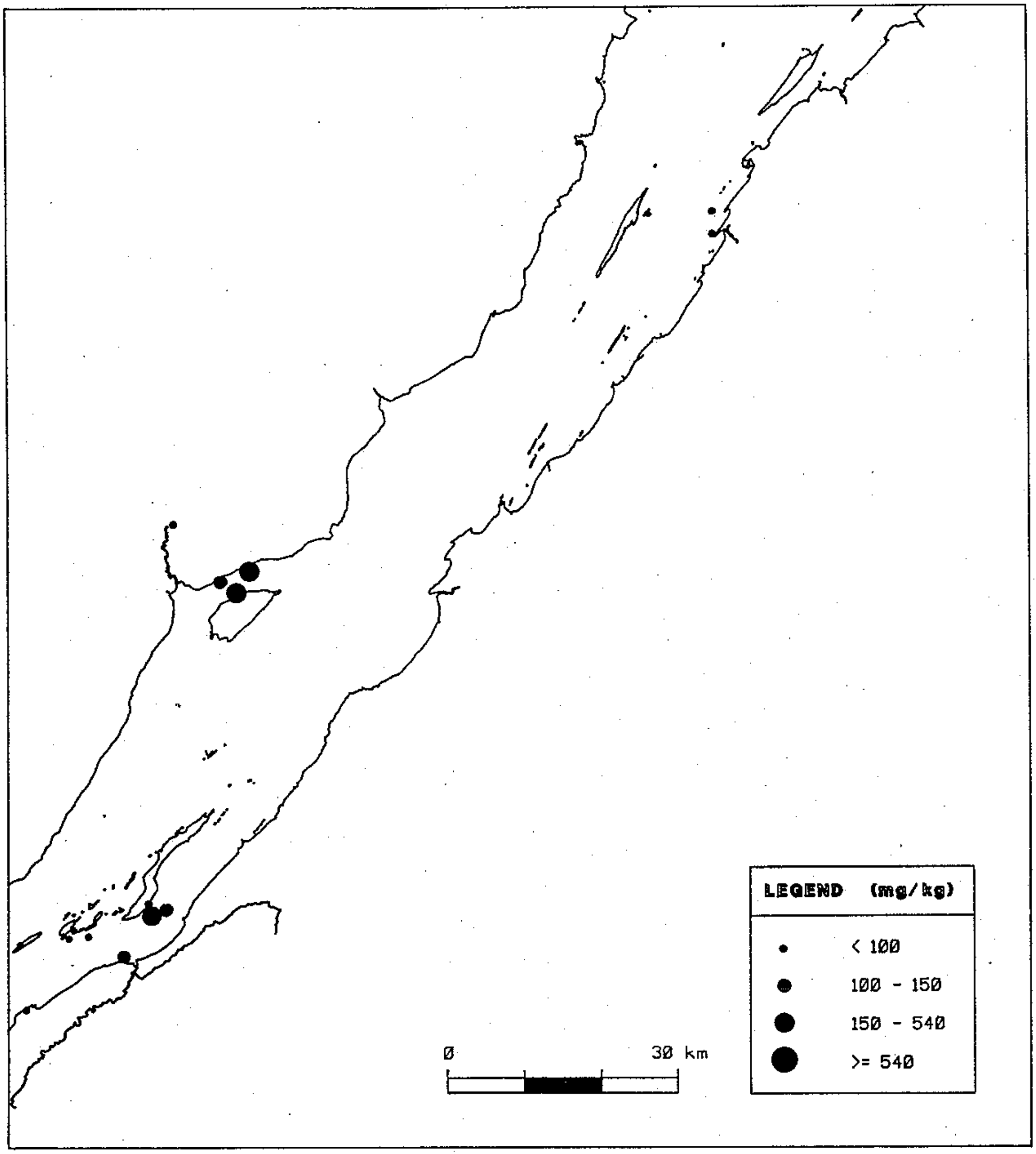


Figure 78 Zinc distribution in upper estuary sediment (1985-1991)

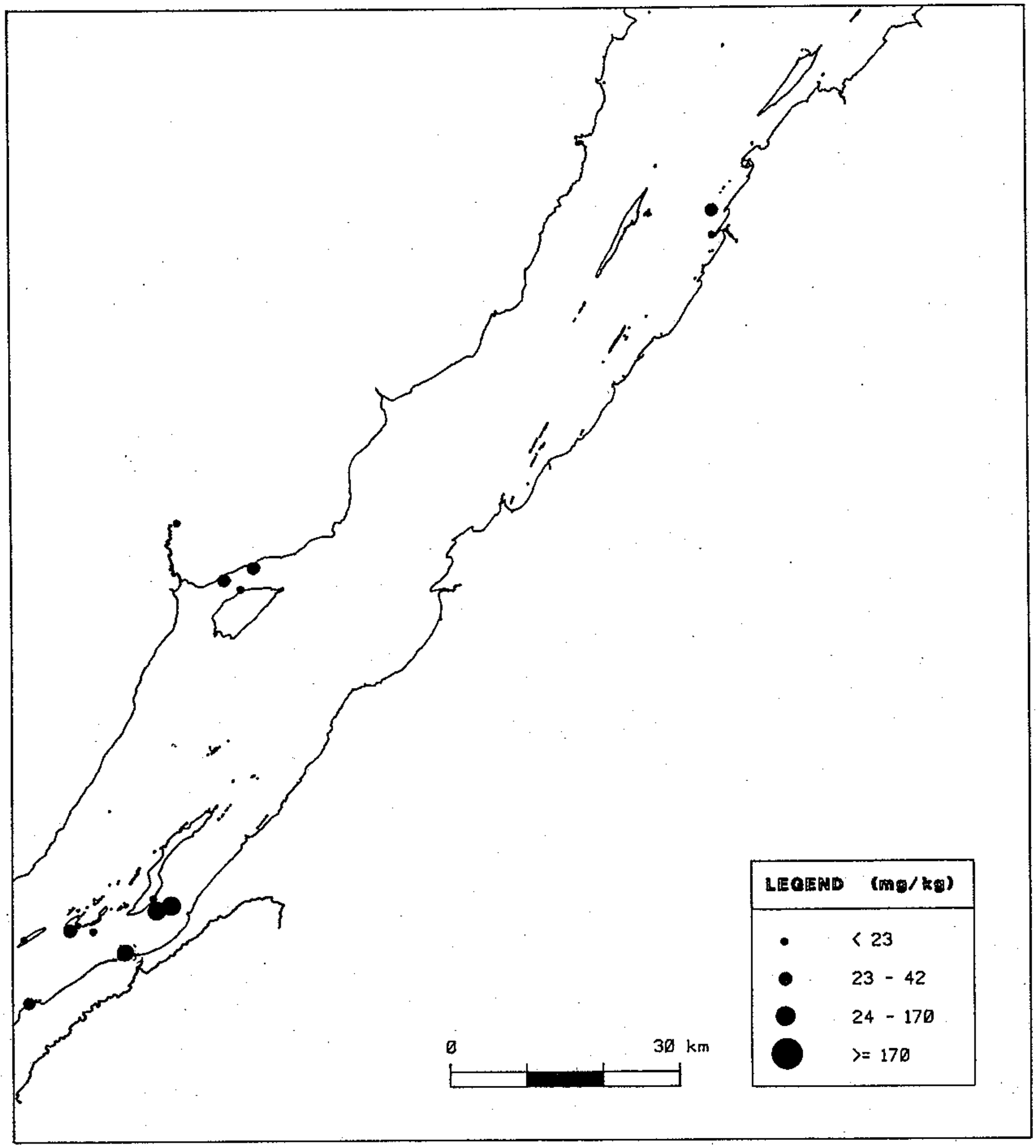


Figure 79 ***Lead distribution in upper estuary sediment (1985-1991)***

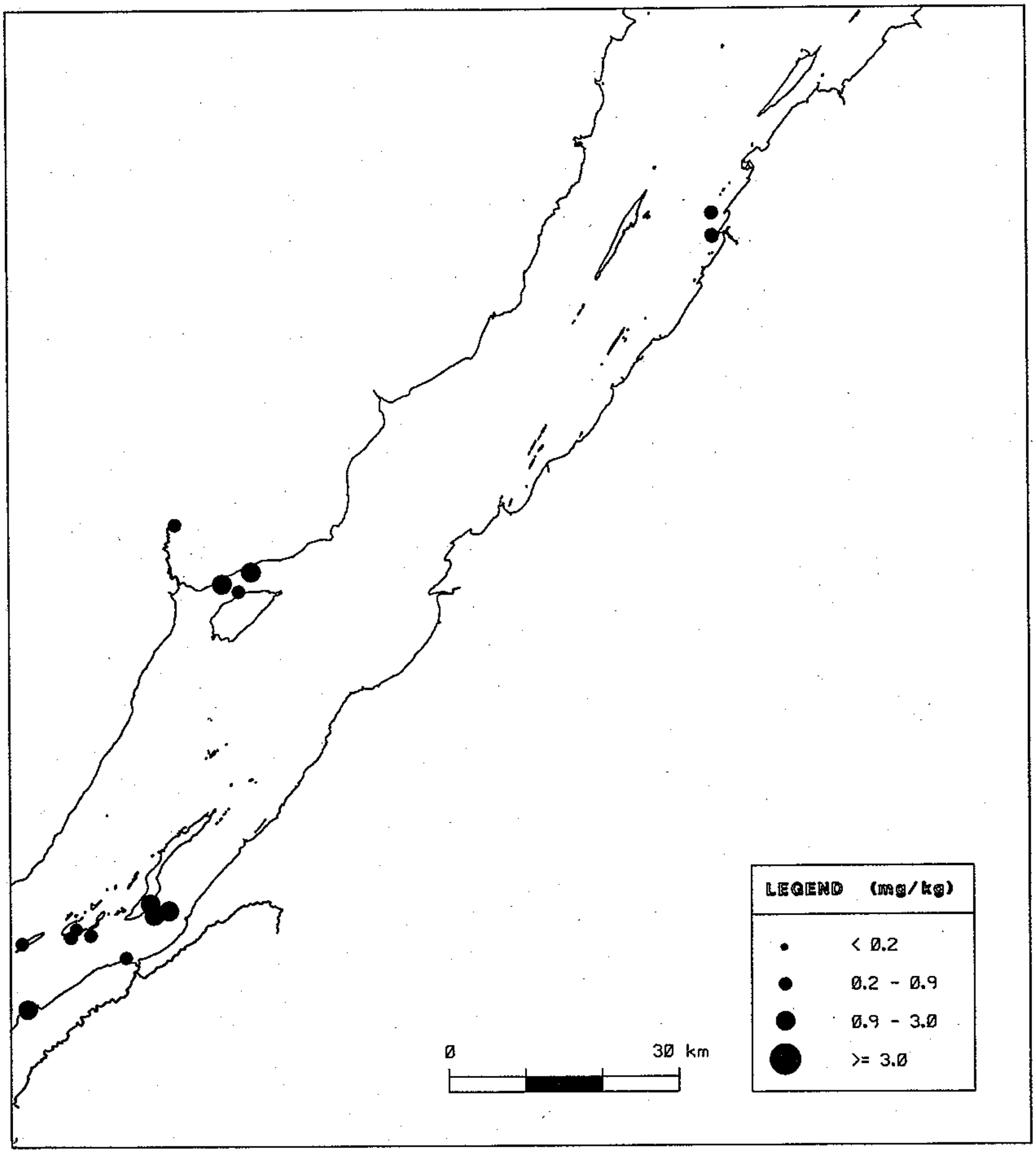


Figure 80 Cadmium distribution in upper estuary sediment (1985-1991)

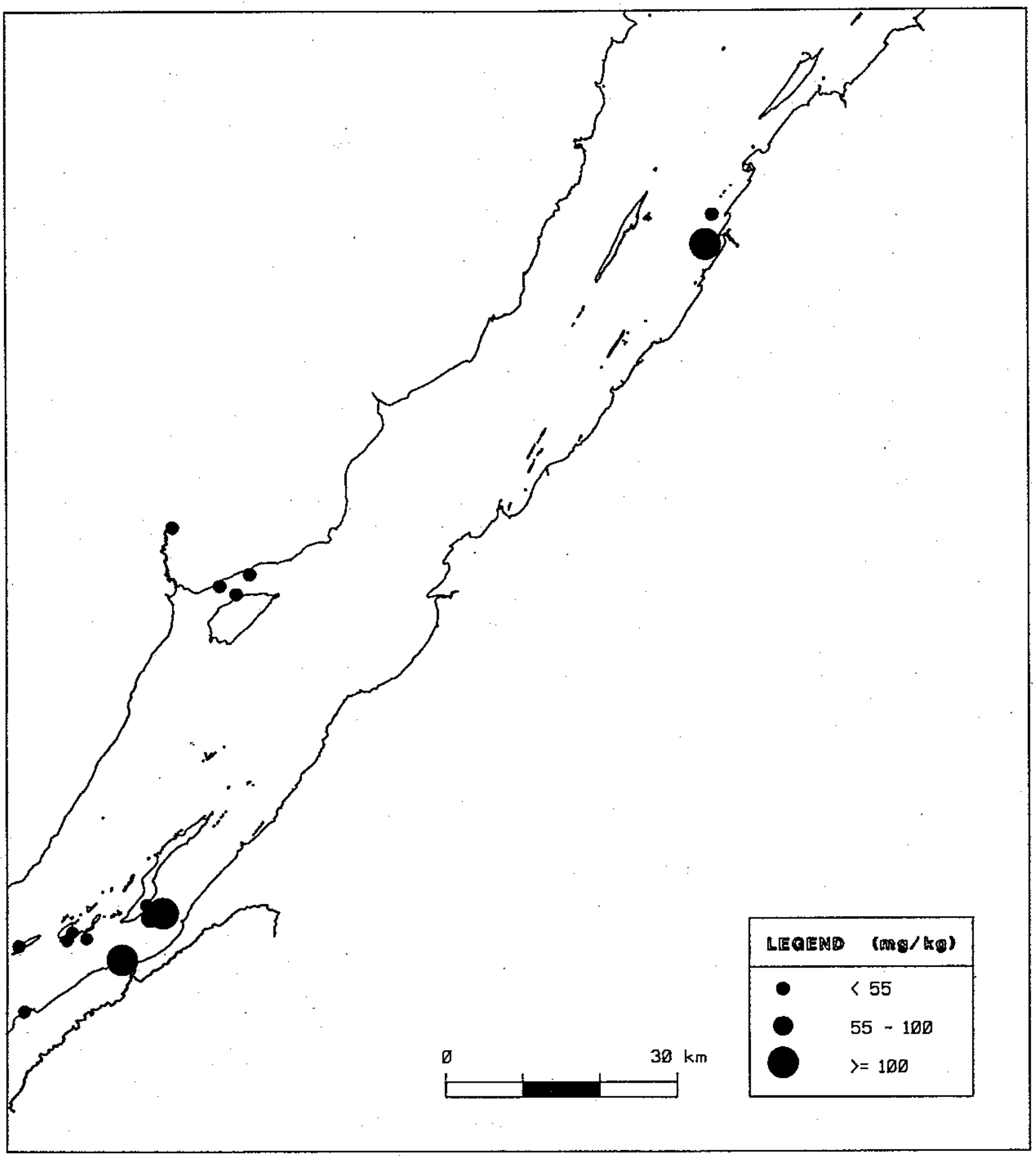


Figure 81 Chromium distribution in upper estuary sediment (1985-1991)

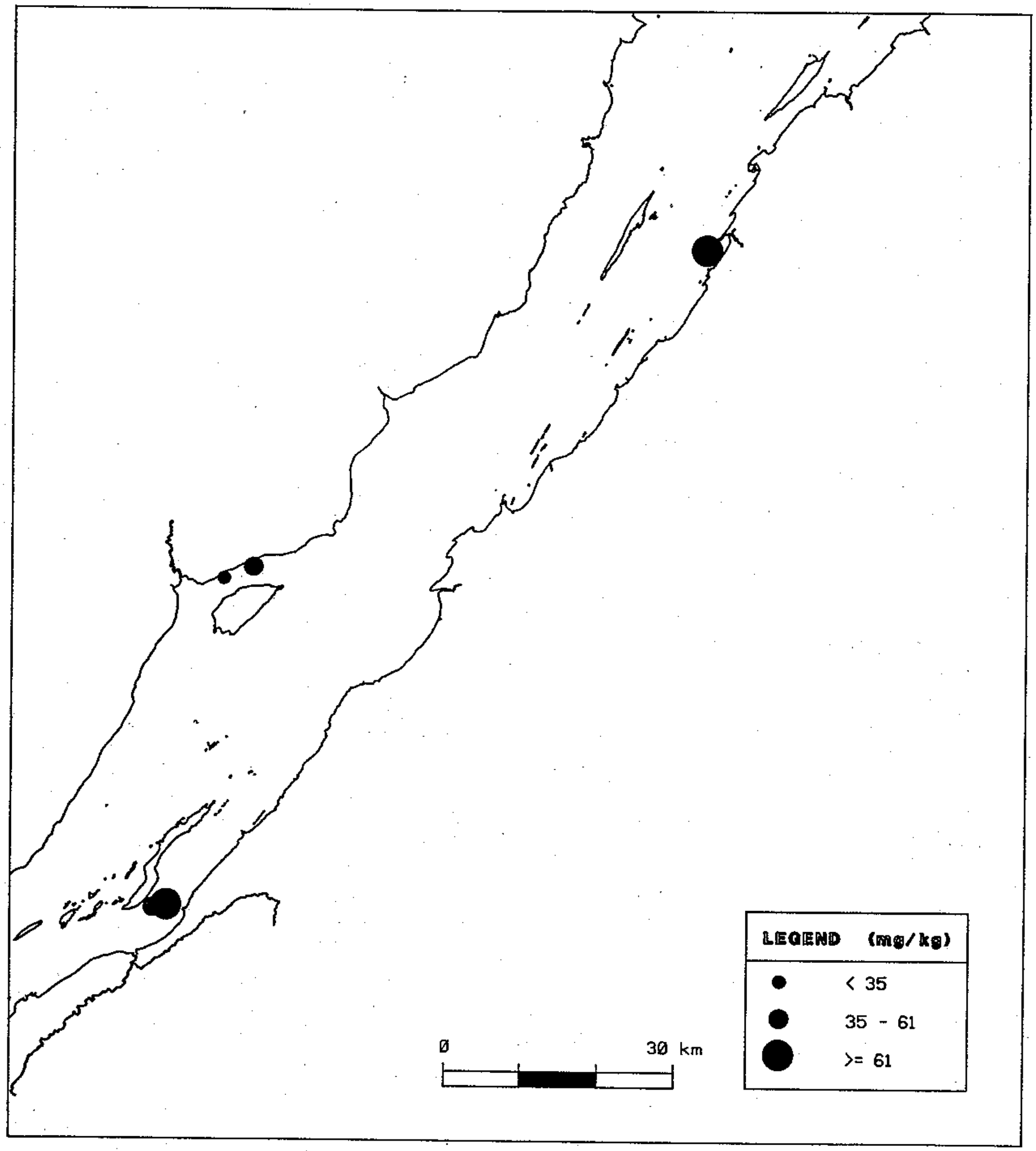


Figure 82 Nickel distribution in upper estuary sediment (1985-1991)

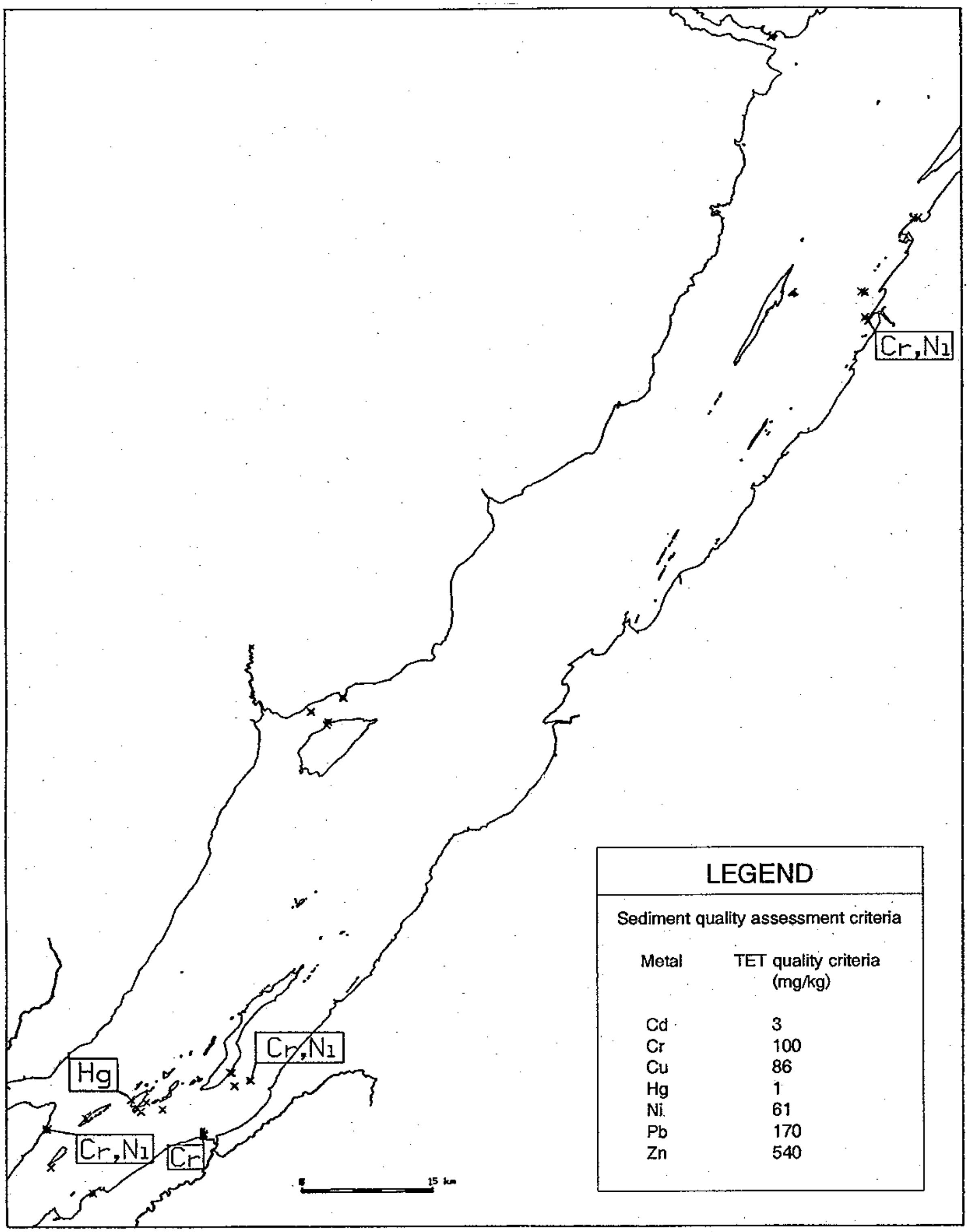


Figure 83 ***Exceedences of TET quality criteria in upper estuary sediment (1985-1991)***

By 1983, more than seven years after the chloralkali plant had closed down, surface sediment mercury content had dropped to moderate levels (0.2 to 0.8 μg/g)--still nonetheless four to seventeen times preindustrial levels (Gobeil et al., 1984). Besides, Pelletier et al. (1988) note the mercury is available for biota, suggesting fjord sediment remains a storage area for large amounts of mercury that seem responsible for persistent contamination of organisms whose diet is linked to the sediment (Cossa, 1990).

Barbeau et al. (1981) noted an increase in anthropogenic copper (15 percent), lead (40 percent) and zinc (15 percent) in the fjord between 1940 and 1976 (Table 48), a trend confirmed by Loring et al. (1983). An increase in anthropogenic cadmium was also noted by Loring et al. (1983); levels rose to ten times natural background. Input of these trace metals, unlike mercury input, has increased constantly since 1940, suggesting major sources of the metals have not yet been checked. These trends were confirmed by Pelletier et al. (1988); they estimate zinc levels increased 20% between 1972 and 1986.

Table 48 Metal (Cu, Pb and Zn) concentration ranges in Saguenay Fjord sediment before and after commissioning of the Arvida chloralkali plant (Barbeau et al., 1981)

Time	Cu (μg/g)	Pb (μg/g)	Zn (μg/g)
Before 1940	5-30	5-38	24-116
After 1940	8-39	5-72	45-201

7 SEDIMENT QUALITY IN THE LOWER ESTUARY

7.1 Subsystem 5: Tadoussac to Pointe des Monts

7.1.1 Physiography and dynamics. The St. Lawrence gets very wide in the lower estuary, between Tadoussac and Pointe des Monts. This last stretch of the estuary is 230 km long and an average 42 km wide. Maximum width (62 km) is at Baie des Anglais, close to Baie Comeau.

The lower estuary is a vast and very deep saltwater body. Physiographically, it is much more like a gulf than an estuary. In fact, there is no real physical barrier between the gulf and the estuary, and this is why the pronounced widening at Pointe des Monts has been selected as the downstream limit of the lower estuary.

Two major physiographic features mark the upstream limit of the lower estuary: the Saguenay estuary, a fjord that runs 320 m deep; and the Laurentian Trough, a submarine valley more than 380 m deep terminating at either end in a sill scarcely 25 m deep. This unusual topography favours upwelling of the nutrient-rich cold waters of the intermediate layer and their mixing with the waters of the St. Lawrence and the Saguenay.

The waters of the St. Lawrence River tend to flow along the south side of the lower estuary, penetrating the gulf via the Laurentian Trough. Strong winds can greatly disturb normal current and surface velocity regime in the lower estuary. Sometimes huge eddies appear, generated by currents and weather conditions (Environment Canada 1991a). These giant vortexes, sometimes 20 to 50 km in circumference, form and break up and reform erratically, generating transverse movements towards both shores of the St. Lawrence. An object placed in the water at Bic, close to Rimouski, for example, could turn up two days later at Forestville on the north shore. In general, however, surface currents induced by prevailing winds most often cause drift to the north shore of the estuary opposite Île du Bic and towards the south at Pointe des Monts.

Tidal range decreases between Île d'Orléans and Pointe des Monts, whereas wave height and wave energy increase. Accordingly, nearshore dynamics are dominated by tides at the head of the upper estuary (where there are numerous intertidal marshes) and by waves at the mouth of the lower estuary (where there are sandy beaches). These two factors make erosion and sedimentation dynamics of the St. Lawrence estuary unique (Drapeau, 1990).

Though the upper estuary is rarely more than 30 m deep, the Laurentian Trough runs 300 to 350 m deep in the lower estuary. The lower estuary is thus a vast sedimentation area; accumulation rate is about 1.5 to 4 mm/a. Particle distribution and transportation pattern are determined mainly by vertical structure of the water mass, which divides into three layers during the summer season with input from the upper estuary and the Saguenay and biological production. A significant part of the 3 600 000 t of suspended sediment supplied by the upper estuary settles in the lower estuary every year. Basic particle composition mainly reflects erosion of deposits of the Champlain and Goldthwait seas in the St. Lawrence lowlands; composition is also influenced by geochemical transformations that take place during estuarine mixing and as a result of biological processes (D'Anglejan, 1990).

Exchange of sediment between the intertidal zones and the deep channels is an important sedimentological process throughout the St. Lawrence estuary. The principal variables in nearshore sediment dynamics of the upper and lower estuaries are waves, ice and the semidiurnal and semimonthly (neap/spring) tides. These variables control schorre erosion and trapping of suspended matter in the intertidal zones (Troude and Sérodes, 1988).

The Saguenay, Betsiamites, Outardes and Manicouagan rivers are the main tributaries to the St. Lawrence River downstream of Québec City. They also play an important role in nearshore sediment dynamics in the lower estuary. Under natural conditions, these tributaries were a major source of sediment input to the St. Lawrence

River. The rivers have been harnessed, however, and their flow regulated, and the effects of this are not yet completely understood.

Ice also plays an important role in nearshore sediment dynamics. In winter, ice protects the intertidal zone. During spring breakup, ice transports millions of tonnes of fine sediment to the gulf (Troude and Sérodes, 1988). Besides transporting sediment, the drifting ice also erodes the nearshore, especially the intertidal marshes where erosional grooves and shallow pans have been noted (Dionne and Brodeur, 1988).

7.1.2 Sources of contamination. The lower estuary and the gulf are exclusively saltwater. Their drainage areas are mainly on the north shore; they receive discharges of the Saguenay, Manicouagan, Outardes and Moisie rivers among others. Tidal effects largely dominate river discharges in this area, which partly explains the lower density of contaminated sites.

Apart from toxic input from upstream reaches of the St. Lawrence River (the main source of contamination for the whole of the estuary), there are a few point sources in the lower estuary that may have a local impact on sediment quality (Lavalin Environnement, 1989).

Main potential sources on the south shore are municipal discharges from Trois Pistoles, Rimouski, Métis sur Mer and Matane. The harbours and marinas of these three towns are also major potential sources of contamination.

Municipal discharges and pleasure boating are significant potential sources of toxic input on the north shore. In Baie Comeau, metal and organic input from industrial effluents and from waste and residue storage areas of the Compagnie de Papiers Québec et Ontario and Reynolds Canada contribute to contamination detected in Baie des Anglais, close to Baie Comeau. Other sources of toxic input are the Baie Comeau municipality and possibly federal and private harbours, the marina and ferry activities.

7.1.3 Particle-size distribution. Figure 94 (included in section 8.3) shows dominant size fractions in the lower estuary. As the figure shows, most of the estuary floor is occupied by fine material.

Figure 84, generated from Dragsed data, shows dominant size fractions at each sampling station. This site-specific data confirms the dominance of fine material on the floor and in nearshore areas of the lower estuary.

Saltwater cord-grass marshes cover some 44 km^2 between Baie St. Paul and Pointe des Monts: 12 km^2 along the north shore of the estuary, 30 km^2 along the south shore and 2 km^2 around Île aux Coudres and Île Verte. Apart from these marshes, the north shore of the estuary consists of sand beaches alternating with granite seacliffs. Beaches at the mouth of the estuary are more like marine than estuarine beaches, because wave energy levels at the mouth of the estuary are comparatively high for an estuarine environment (Drapeau, 1990).

7.1.4 Physical chemistry. Moderate contamination by anthropogenic mercury (0.03 to 0.95 μg/g) was detected in surface sediment of the lower estuary before 1975; distribution was linked to the pattern of deposition of organic matter originating in the Saguenay (Loring, 1975). Gobeil et al. (1989) noted a downward trend in concentrations; by 1987, mercury levels had dropped to 0.16 to 0.18 μg/g. Because of the low concentration gradient measured at the water-sediment interface, Gobeil et al. (1989) concluded that in this environment there is little transport of mercury out of sediment by diffusion.

Loring (1978a, 1979) measured concentrations of five other trace metals. He discovered slight chromium, lead and zinc enrichment of sediment in the lower estuary (Table 49). Other metals were generally at natural background levels. The greatest enrichment by copper, lead and zinc was detected in the fine sediment of the central valleys and of certain shelves. Most of the sandy shelves are slightly contaminated by these metals. Data collected by Gobeil (1991) show the same trends (Table 50).

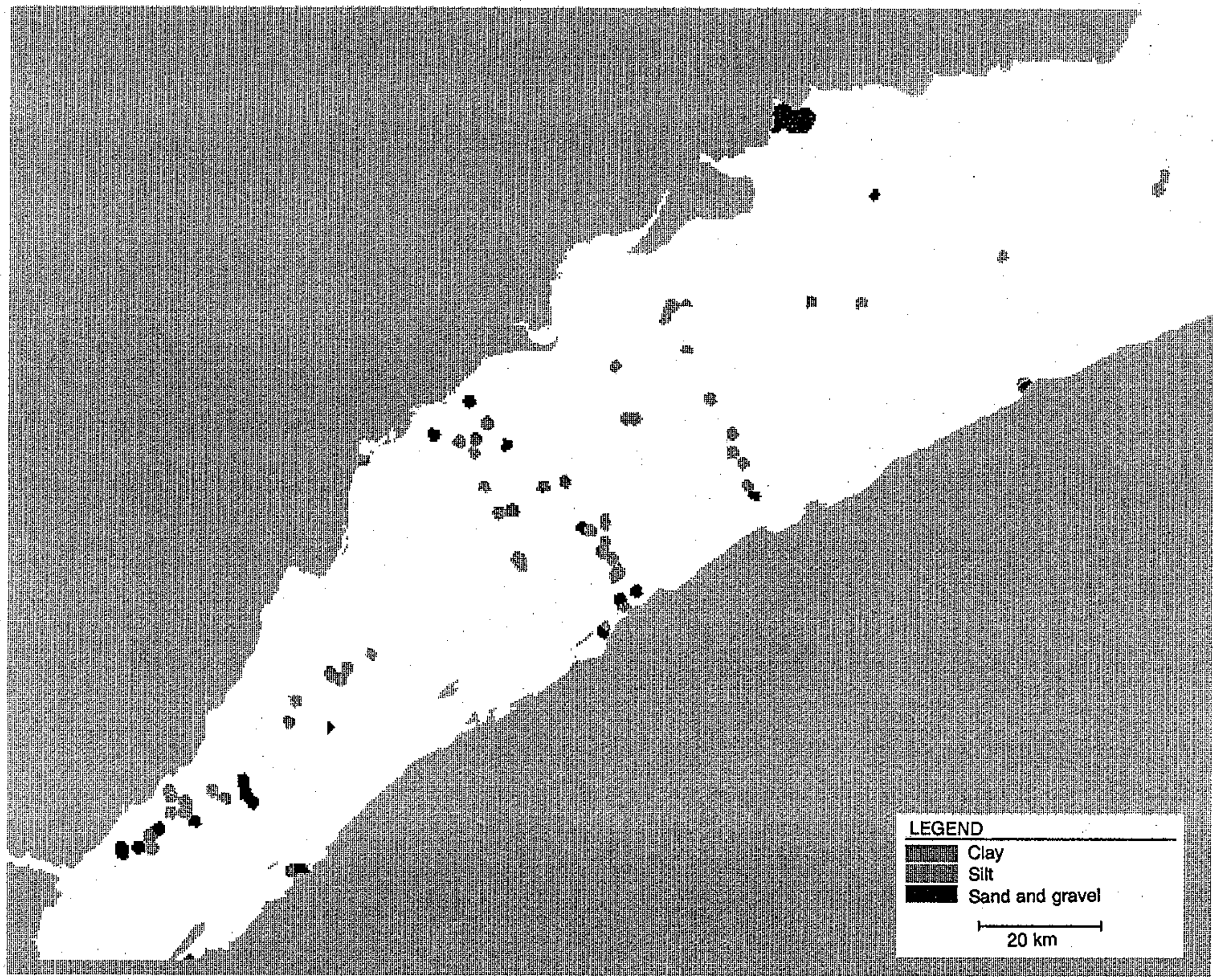


Figure 84 ***Dominant size fractions in the lower estuary***

Table 49 ***Mean metal (Cr, Cu, Ni, Pb and Zn) concentrations and standard deviations in surface sediment of the lower estuary (Loring 1978a, 1979)***

Location	Cr (µg/g)	Cu (µg/g)	Ni (µg/g)	Pb (µg/g)	Zn (µg/g)
Lower estuary	99 ± 12.3	24 ± 7.2	33 ± 6.2	30 ± 8.0	115 ± 20

Table 50 ***Sediment quality in the Laurentian Trough (lower estuary) (after Gobeil, 1991)***

Metal	Concentration (µg/g)	NET criterion	MET criterion	TET criterion
Lead	43	23	42	170
Cadmium	0.16	0.2	0.9	3
Mercury	0.17	0.05	0.2	1
Zinc	164	100	150	540
Copper	22	28	28	86

As for spatial trends, total copper, zinc and to a lesser extent lead concentrations in the pelites decrease from the upper estuary seaward. The reverse is true of nickel. Chromium levels are higher in the lower estuary and the gulf than in the upper estuary and the Saguenay Fjord.

The lower estuary is enriched by bioavailable copper, lead and zinc in contaminated fine sediment that has escaped from the upper estuary and in organic matter (contaminated by mercury as well) from the Saguenay Fjord. This material settles in the deepest parts of the upper estuary from where it has little chance of escaping. Bioavailable nickel and chromium come mainly from the lower estuary (Loring, 1978a and 1979).

At the few lower estuary nearshore stations for which data are available in Dragsed, sediment quality is good to acceptable (figures 85 to 91), except in Baie Comeau, where high mercury levels were detected (Table 51). The contamination is localized, however, and may be associated with local industrial or harbour activities and municipal discharges.

Table 51 Extremes recorded in nearshore lower estuary sediment

Site	Year	Metal	TET criterion (µg/g)	Concentration (µg/g)
Baie Comeau (Baie des Anglais)	85	Hg	1	1.21

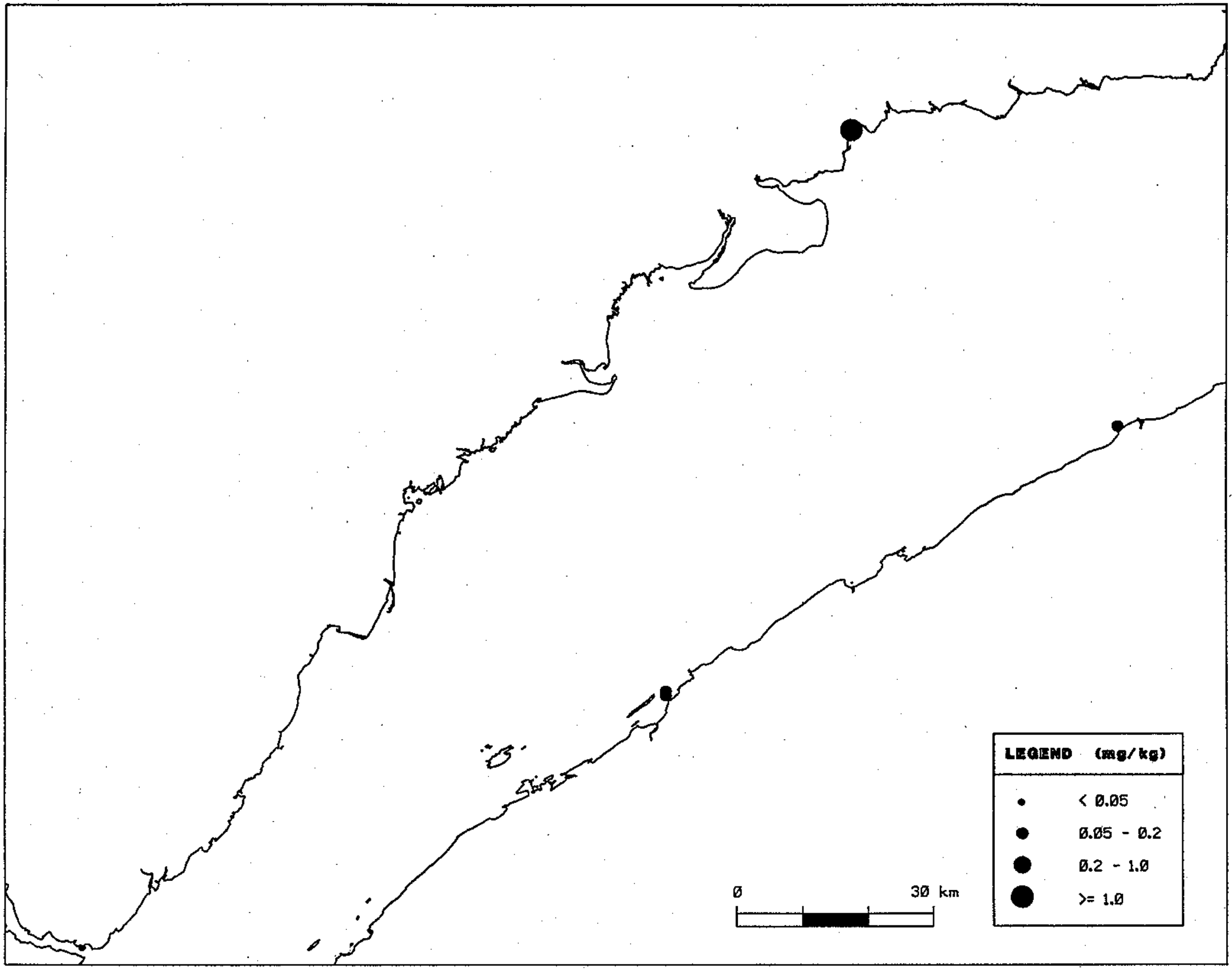


Figure 85 Mercury distribution in lower estuary sediment (1985-1991)

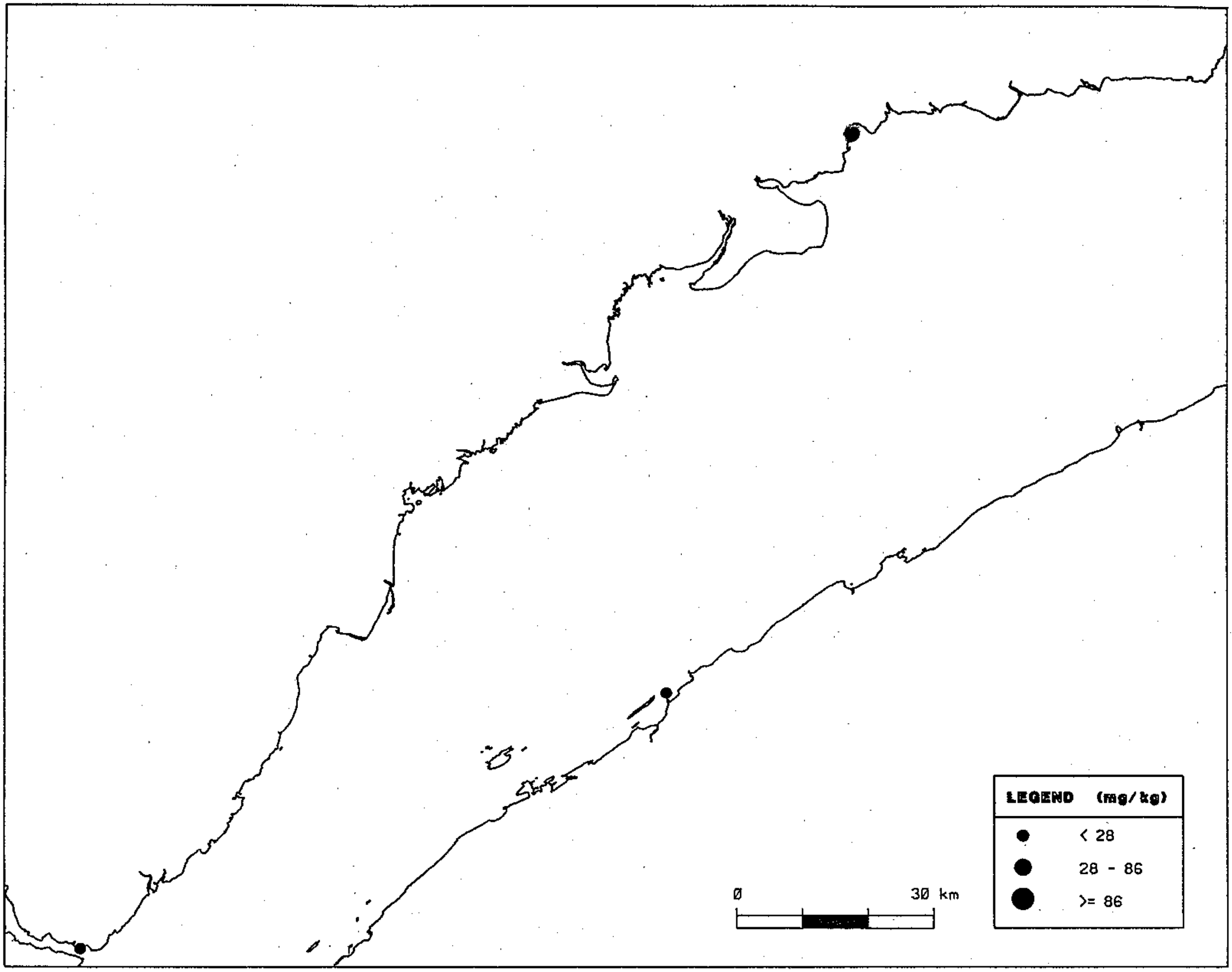


Figure 86 Copper distribution in lower estuary sediment (1985-1991)

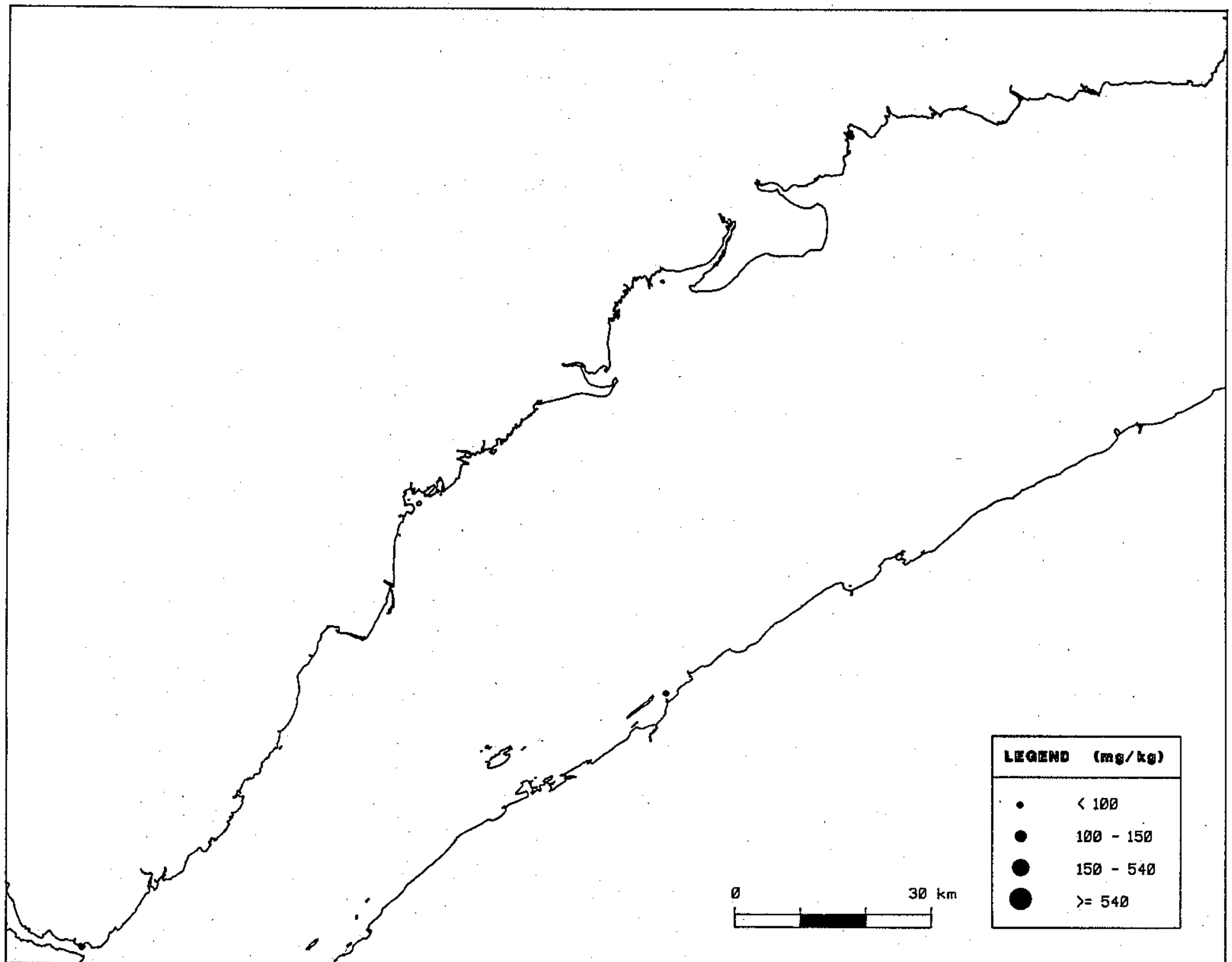


Figure 87 *Zinc distribution in lower estuary sediment (1985-1991)*

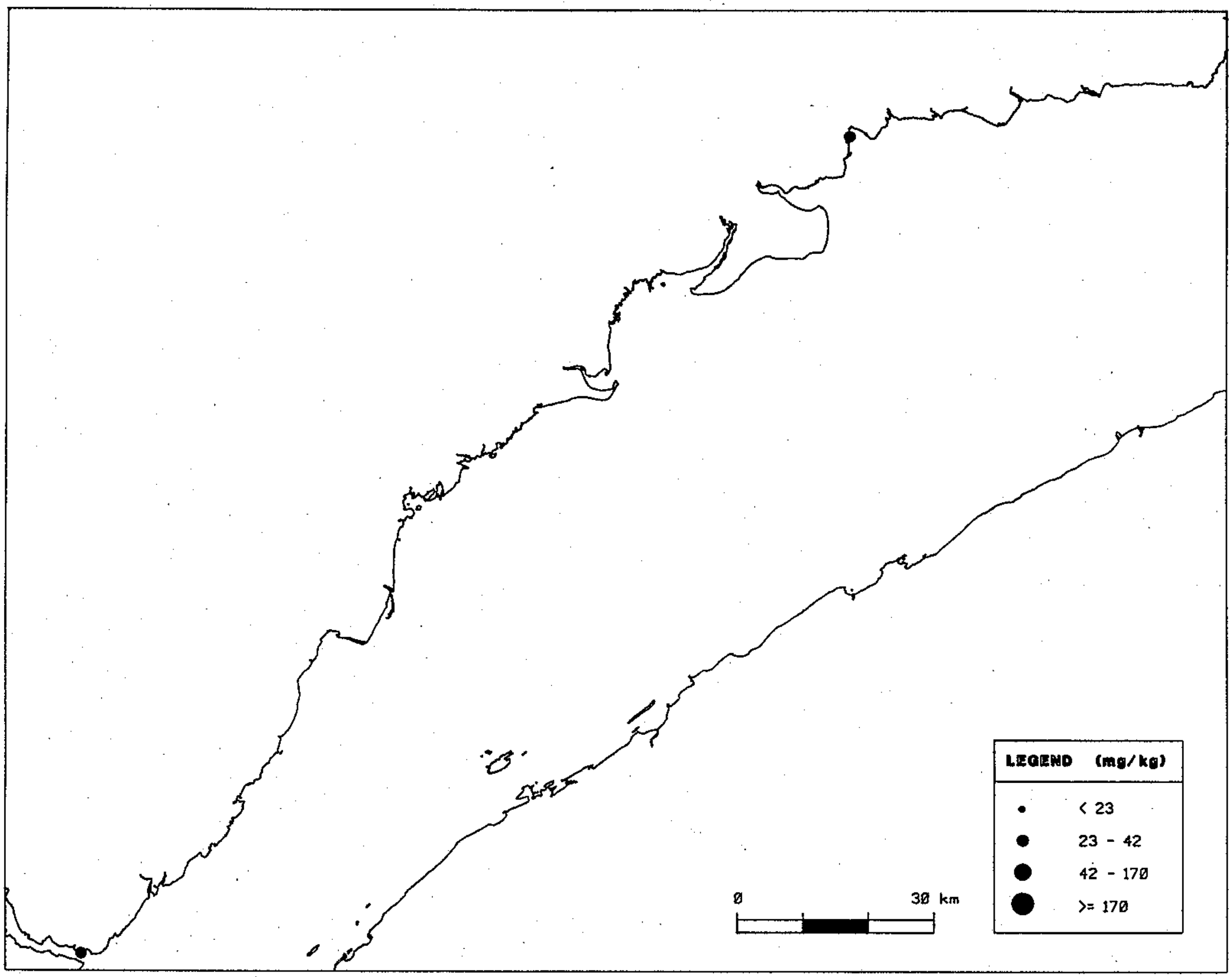


Figure 88 Lead distribution in lower estuary sediment (1985-1991)

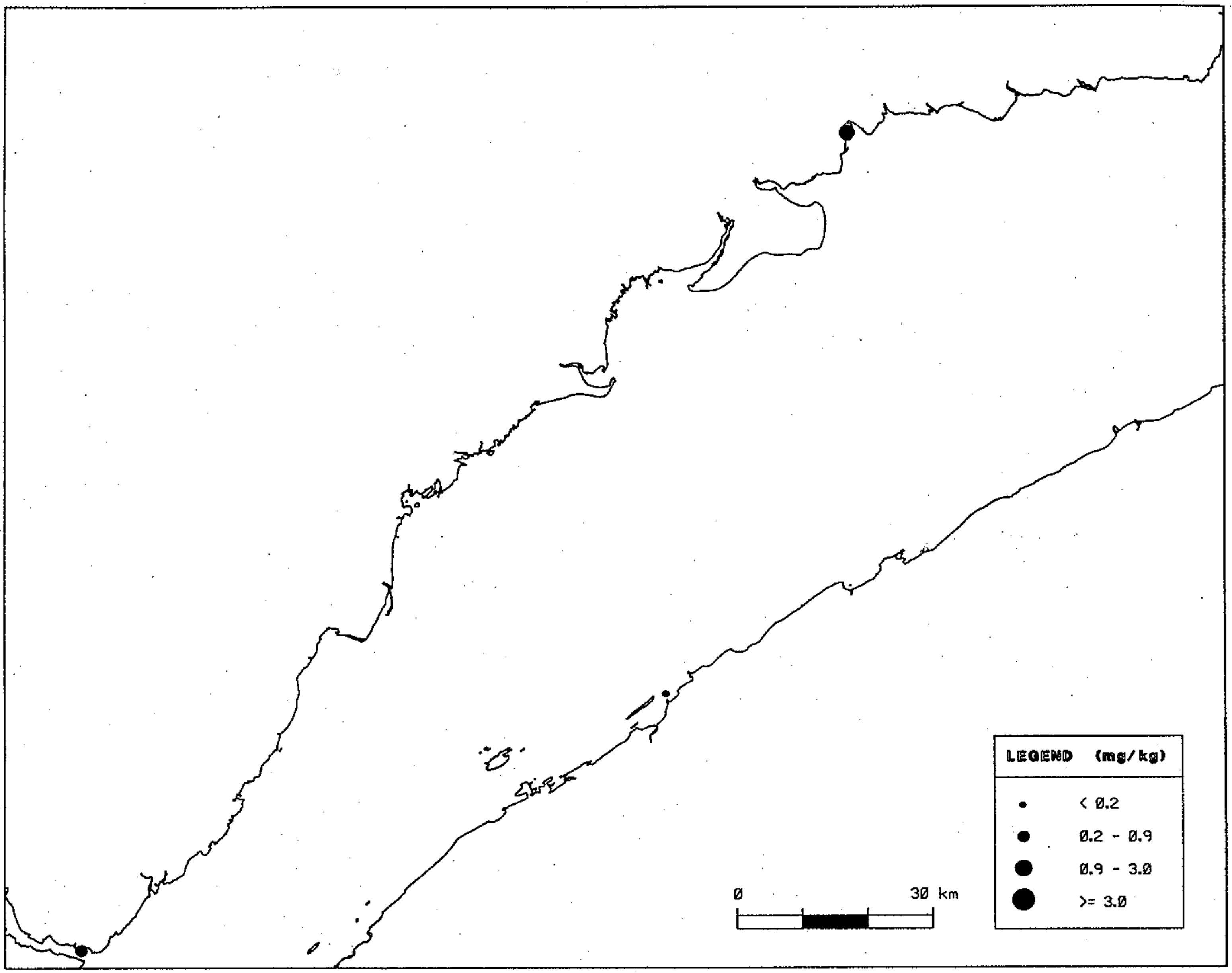


Figure 89 Cadmium distribution in lower estuary sediment (1985-1991)

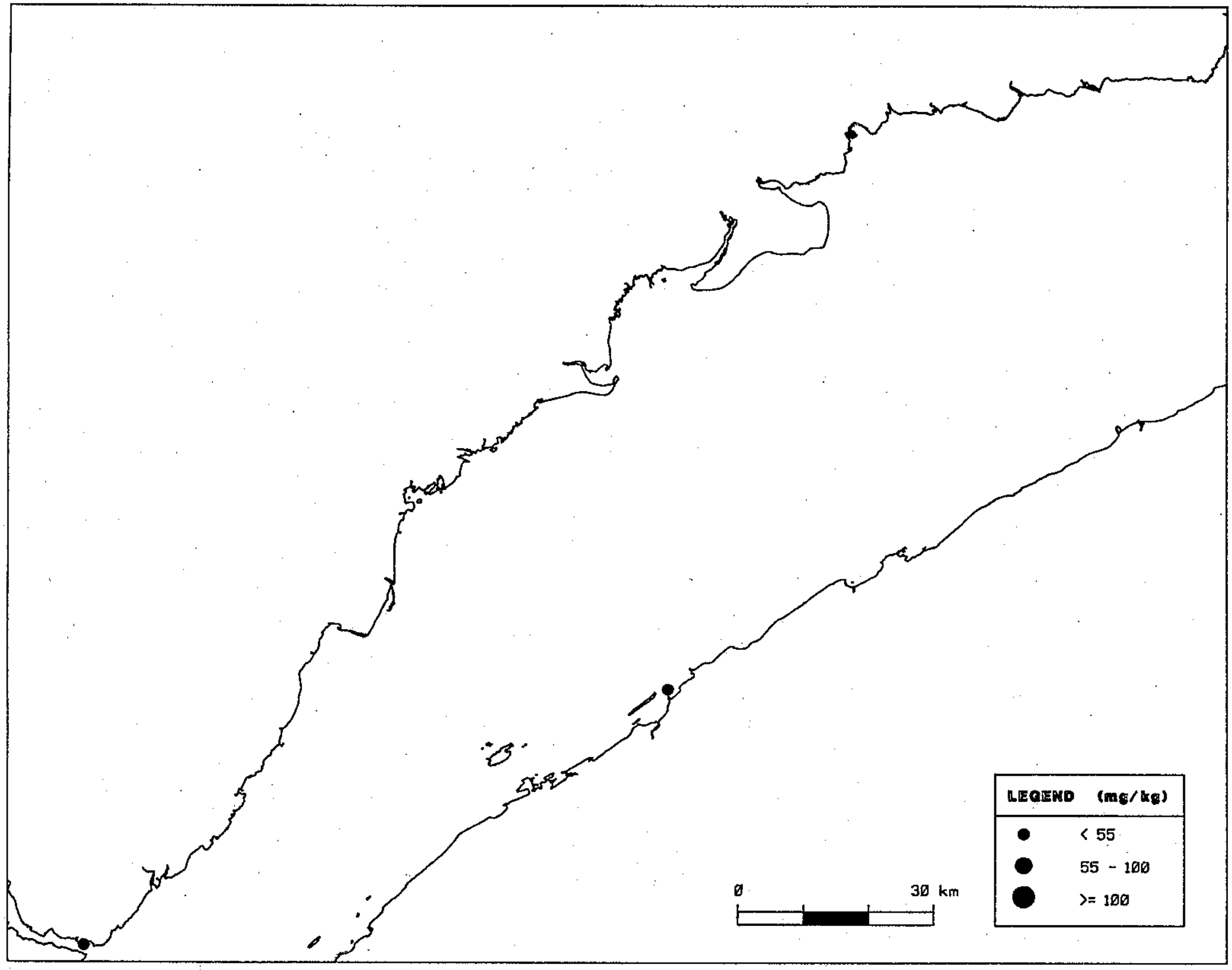


Figure 90 Chromium distribution in lower estuary sediment (1985-1991)

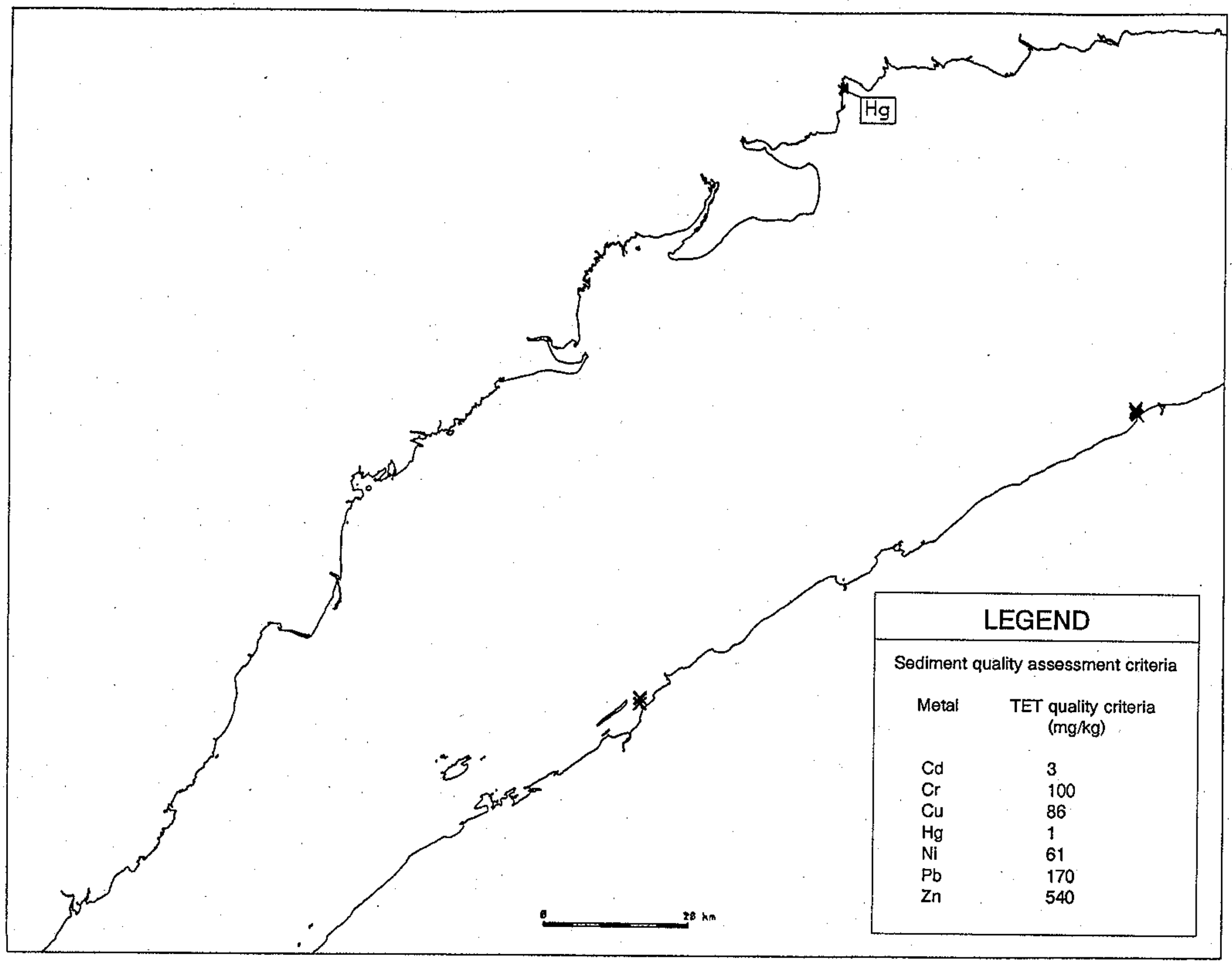


Figure 91 Exceedences of TET quality criteria in lower estuary sediment (1985-1991)

8.1 Subsystem 6: Pointe des Monts to Newfoundland (including the Magdalen Islands)

8.1.1 Physiography and dynamics. The St. Lawrence River finally empties into an immense gulf of over 195 000 km^2; by way of comparison, surface area of the lower estuary is 12 600 km^2. Downstream of Tadoussac, the Laurentian Trough plunges rapidly to a depth of 350 m and generally remains more than 300 m deep thereafter. Close to Cabot Strait, the gulf is sometimes more than 500 m deep. Elsewhere, the gulf is 100 to 400 m deep, except on the Magdalen Shelf, which is rarely more than 70 m deep.

As Figure 92 shows, the gulf is composed of a network of long submarine valleys, shelves and banks.

The Laurentian Trough is the largest of the submarine valleys. It is 1240 km long (from the mouth of the Saguenay to the edge of the continental shelf) and 200 to 540 m deep. Southwest of Anticosti Island, the Laurentian trough connects with two other valleys--the Anticosti Trough from the northwest, and the Esquiman Trough from the northeast. Both these troughs are 200 to 300 m deep. Smaller valleys such as the Cape Breton Trough and the trough that comes from the south side of Newfoundland (maximum depth is 360 m) also connect with the Laurentian Trough. The troughs are characteristically wide with steep walls and irregular bottoms (depressions can run as much as 100 m deep).

The shelves that accompany the network of troughs divide into five main units:

- The shelf on the north side of the St. Lawrence that runs from Sept Îles to Cape Whittle
- The Québec-Labrador Shelf that runs from Cape Whittle to the Strait of Belle Isle

These two shelves are narrow and run along the coast.

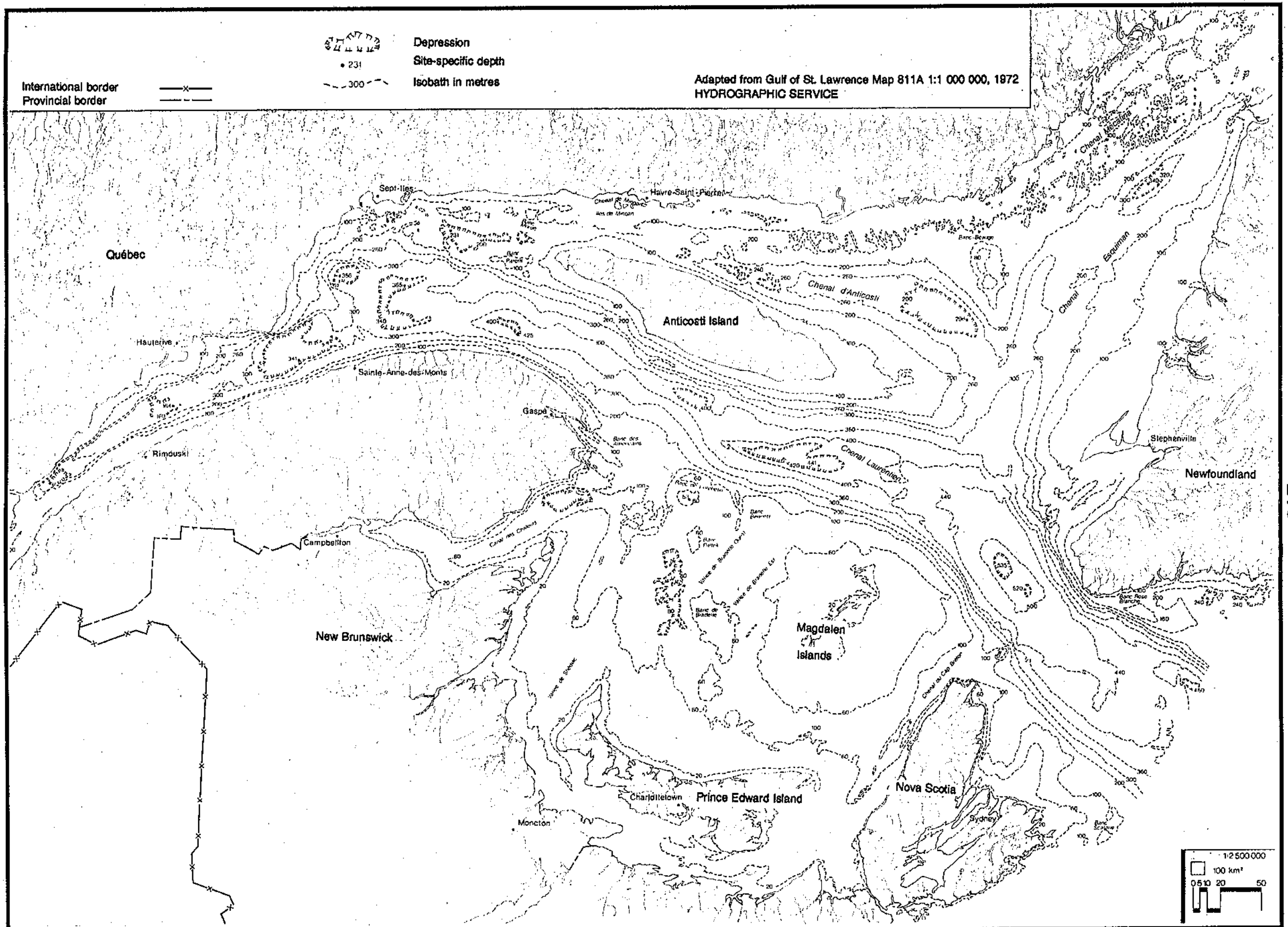


Figure 92 Bathymetry of the Gulf of St. Lawrence (after Roche Associés, 1983)

- The Newfoundland Shelf that runs along the west coast of Newfoundland
- The Anticosti Shelf, an extension of Anticosti Island and the Newfoundland Shelf
- The Magdalen Shelf, the largest of the shelves, in the southern part of the gulf (depths are 10 to 20 m)

Islands are relatively small in the estuary, but the gulf has a number of major islands: Anticosti Island, the Magdalen Islands, Bonaventure Island, the Mingan Archipelago and the Sept Îles archipelago.

Circulation and mixing of water masses in the gulf are complex because there are so many determining factors: tides, atmospheric pressure, air temperature, wind, local freshwater inflows, bathymetry, coast topography and the earth's rotation (Dunbar et al., 1980).

Current data collected by Trites (1972) and El-Sabh (1976) and compiled by Roche Associés (1983) give a general picture of dominant surface-current trajectories in the gulf. The paths are dominated by St. Lawrence River discharge and by water mass transfers at the dividing line between the ocean and the gulf.

During the ice-free period, discharge of the St. Lawrence River drives a pair of coastal jets that form the Gaspé current. Originating around Rimouski, the Gaspé current runs along the south shore of the estuary and turns south at the tip of the Gaspé peninsula. In the Gaspé passage, velocity is 20 to 70 cm /s 5 km from the south coast, diminishing to zero about 30 km from the coast.

In Cabot Strait, outgoing current dominates, spreading over most of the south side of the passage the length of Cape Breton Island. Velocities reach a maximum (20 to 70 cm/s) close to the northern tip of Cape Breton Island and decrease seaward. On the north side of the strait, a slow incoming current (5 to 15 cm/s) is generally noted close to Port aux Basques. This current seems to be the end of the Labrador stream after it has run along the east coast of Newfoundland.

Circulation pattern is similar in the Strait of Belle Isle. Water masses from the central and eastern part of the gulf flow to the Atlantic while part of the Labrador stream enters the gulf via the strait. Mean velocity of the outgoing current is 20 to 30 cm/s with maximum velocities along the coast of Newfoundland. Mean velocity of the incoming current is 10 to 20 cm/s.

Water exchanges in these three passages seem to determine general circulation pattern in the gulf. Circulation pattern in the central part of the gulf is cyclonic. Currents enter by the Strait of Belle Isle, run west along the north coast, turn south at Sept Îles and finally meet up with the Gaspé current returning southeast. Part of the Gaspé current runs through the centre of the gulf, combines with waters penetrating through Cabot Strait and follows the west coast of Newfoundland to the entrance to the Strait of Belle Isle. At this point, the flow divides, part running into the ocean and the rest mixing with the incoming current.

The other part of the Gaspé current runs along the shores of New Brunswick and enters Northumberland Strait and the passage between the Magdalen Islands and Prince Edward Island. These waters generally run east and eventually leave the gulf through Cabot Strait. At the western entrance to Northumberland Strait, some of the flow penetrates the strait but the rest runs north along the coast of Prince Edward Island and then into Cabot Strait. The flow that penetrates Northumberland Strait is weak. When it leaves the strait it turns towards the southwestern end of Newfoundland before emptying into the ocean via Cabot Strait.

Though little information is available, winter circulation pattern clearly differs from circulation during the ice-free period. In the centre of the gulf, currents are weaker and their spatial distribution is more irregular in winter. In the southern part of the gulf, directions of flow are similar to trajectories noted during the ice-free period, though the outgoing current of Cabot Strait seems to concentrate along either side of the strait in winter with a strong incoming current running through the centre. Outgoing current velocity is 10 to 20 cm/s on the Cape Breton Island side but slower on the Newfoundland side. The ocean current penetrates at a speed of 10 to 30 cm/s. The current along the north side derives from the descent of water masses along the west coast of Newfoundland.

Between Anticosti Island and the coast of Québec, currents run east in the winter and then south to Cabot Strait.

There are also a number of distinct, periodic local movement systems in addition to the general annual pattern of current trajectories. El-Sabh (1975) demonstrates there are clockwise and anticlockwise eddies in the gulf--some semipermanent and others that last only a few days or a few weeks, some stationary and others that move with the currents. Koutitonsky and Bugden (1991) say the eddies are synoptic phenomena that last only a few days.

Other local variations are typical of surface currents in general. In open areas of the gulf, velocities are slow and current direction is readily affected by disturbed weather. Even where velocities are fast, current directions are not stable. Major variations have been noted in Cabot Strait and the Gaspé current.

Waves are 2 m high 5 to 40 percent of the time between Tadoussac and Pointe des Monts, where the estuary is 60 km wide and 350 m deep in the centre of the Laurentian Trough. Waves are 5 m high once a year and can reach 7 m during exceptional storms (Ouellet and Llamas, 1979).

Throughout the St. Lawrence system, water levels are influenced by tide propagation. Tidal fluctuations in the gulf and the St. Lawrence estuary are generated by tide waves that penetrate the straits of Cabot and Belle Isle and propagate upstream. Since the gulf is so large, tides develop within the gulf itself. However, the main source of tide propagation through the gulf and the estuary is the tide wave that penetrates Cabot Strait. The Strait of Belle Isle has much less impact on tidal behaviour of the St. Lawrence system as a whole; tides that enter this strait have a local and limited impact only.

Average tide range is 2.3 m at Sept Îles, and only increases 0.7 to 3.0 m between Sept Îles and Pointe au Père (Fisheries and Oceans Canada, 1992). Tide range is greatest around Île d'Orléans, just before penetration of the riverine estuary.

There have been a number of studies about the tidal regime of the Gulf of St. Lawrence. Godin (1979) summarizes current knowledge of tides in the Gulf of St. Lawrence and the St. Lawrence estuary. Tidal regime in the gulf and the estuary is influenced by diurnal and semidiurnal tides penetrating Cabot Strait. The semidiurnal component dominates gulf tides. The rising tide penetrates Cabot Strait and turns around two amphidromic points in the gulf, one close to the Magdalen Islands and the other at the west end of Northumberland Strait. At these points, amplitude of the semidiurnal tidal component is negligible, and the tide is a function only of the diurnal component, whose amphidromic point is outside the gulf, somewhere between Cape Breton Island and Sable Island; the tide penetrates obliquely into Cabot Strait and runs northwest to Anticosti Island and southwest towards Prince Edward Island.

Coastal environments differ along the gulf and through the estuary depending on tidal range. In the estuary to Pointe des Monts, the semidiurnal tide wave dominates, generating the gulf's only macrotidal environment. Spring tide range is more than 4 m in this environment.

Microtidal environments, with spring tide ranges of less than 2 m, are typical of most of the gulf, though there are sites where conditions are between macrotidal and microtidal. In the eastern part of the gulf, mean tide range is 0.8 to 1.7 m and the semidiurnal component dominates. Tide range increases along the north side with penetration of the estuary.

In the southern part of the gulf, the tide is mixed and the diurnal component dominates. Environments along the southern coast of the gulf are microtidal with mean tidal ranges between 0.5 m and 2 m.

8.1.2 Sources of contamination. The lower estuary and the gulf are exclusively saltwater. Drainage areas are mainly on the north shore (the Saguenay, Manicouagan, Outardes and Moisie rivers among others). Tidal effects largely dominate river discharges in this area, which partly explains the lower density of contaminated sites.

Apart from toxic input from upstream reaches of the St. Lawrence River (probably the main source of contamination for the whole of the estuary), there are a few point sources in the gulf that may have a local impact on sediment quality (Lavalin Environnement, 1989).

The main potential sources on the north shore are associated with the main municipalities. Potential sources identified at Port Cartier are municipal wastewater discharges and activities associated with the two harbours. The Sept Îles Bay receives municipal wastewater, and along its shores are Iron Ore and Wabush Mines residue and ore storage sites. This bay may also receive input from activities at the Sept Îles harbour, the marina and the fishing port.

The main potential sources on the south shore identified by Lavalin Environnement (1989) are Gaspé municipal effluents and harbour activities, especially those at Sandy Beach (transhipping of copper ore by Gaspé Mines)

The only known contaminated site in the Magdalen Islands identified by Lavalin Environnement (1989) is at Cap aux Meules (Grindstone Island). Potential sources are wastewater discharges from a fish plant and the municipality. There are also three fishing docks and three marinas near by.

8.1.3 Particle-size distribution. Figure 93--adapted by Roche Associé (1983) from maps drafted by Loring and Nota (1973)--shows nature and regional distribution of gulf surface sediment. Surface sediment in the lower estuary and the gulf divide into four main classes: pelites (< 62 μm), sands (0.062 to 2 mm), gravel (>2 mm) and diamicton.

The pelites--30 to 100 percent clay and silt by weight--are found mainly along the floor and the walls of the Laurentian, Anticosti and Esquiman troughs. South

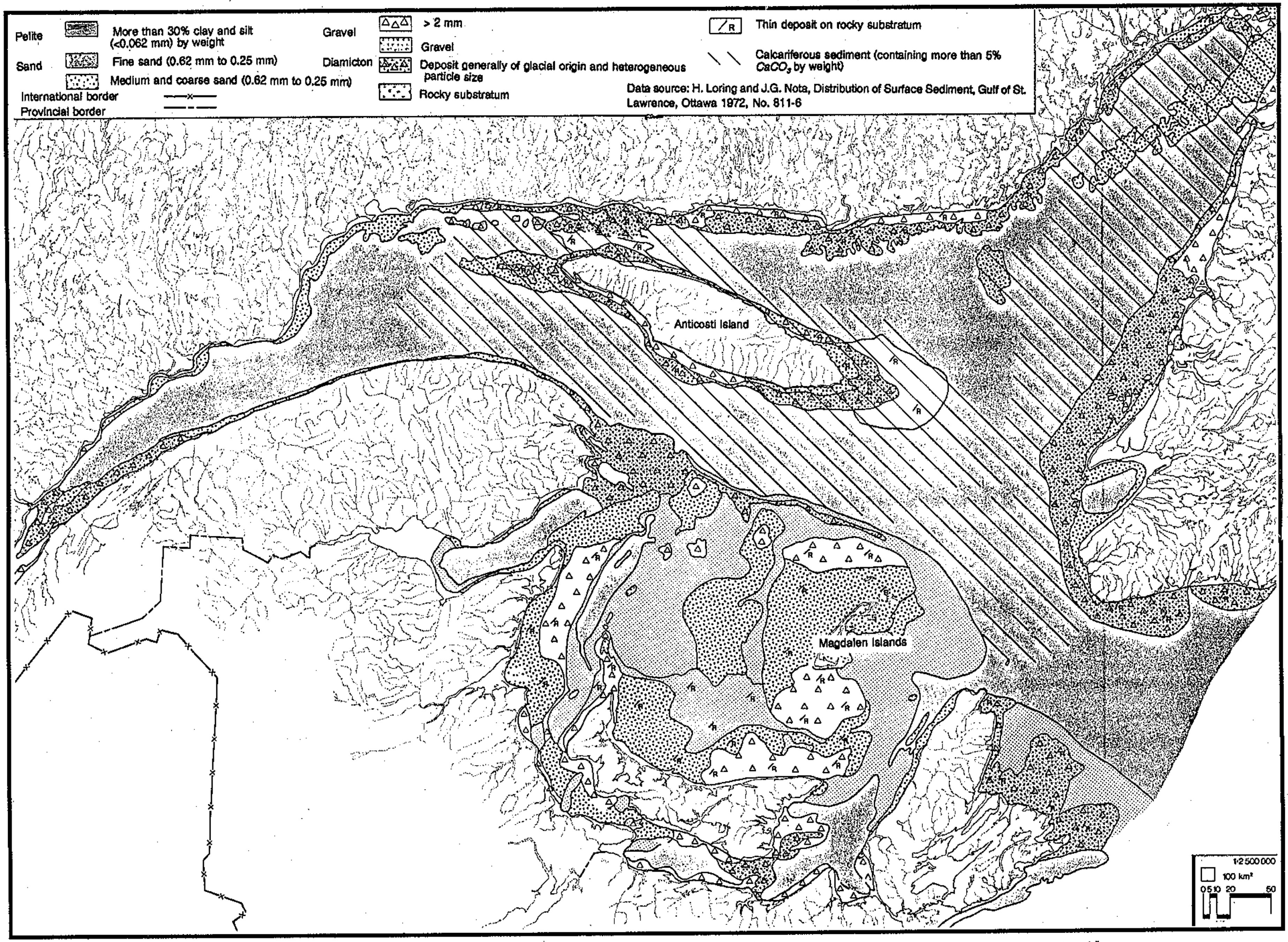


Figure 93 Distribution of surface sediment in the Gulf of St. Lawrence (after Roche Associés, 1983)

of Anticosti Island and along the west coast of Newfoundland, the pelites contain more than 5 percent calcium carbonate ($CaCO_3$) by weight.

The sands subdivide into fine sand (0.062 mm to 0.25 mm), and medium and coarse sand (0.25 mm to 2 mm). Sand and gravel mainly compose the substratum of the Magdalen Shelf. Shell gravel is found in the Strait of Belle Isle and opposite Lourdes de Blanc Sablon.

Generally glacial in origin, diamicton is found mainly along the north shore, around Anticosti Island and along the coast of Newfoundland and Cape Breton Island. Particle size is sometimes very heterogeneous.

Rock substratum outcrops in few places in the gulf, but it is often covered only by a thin layer of loose material, especially in the Magdalen Shelf, around Anticosti Island, along the lower north shore and offshore of Cape Breton Island.

Salt marshes dominate coastal deposits downstream of Pointe des Monts, covering close to 42 km^2 of shoreline along the north shore, the Gaspé peninsula and the Magdalen Islands. The lower parts of the marshes are generally lagoonal environments partially closed off by sand bars and affected by tides of less than 1 m.

The Magdalen Islands are in the centre of a sediment basin, the carboniferous Maritimes basin. Under the Magdalen Islands, sediment deposits are as much as 9 km thick. In addition to very old red sandstone deposits, sand deposits several metres thick have accumulated around the islands more recently with current and wave action, forming long beaches.

Composed of rock outcrops, the Magdalen Islands are connected to one another by double bar tombolos creating lagoons less than 10 m deep but covering dozens of square kilometres. Beaches along the ocean are of medium sand but the sand within the lagoons and bordering them is slightly finer.

Figures 94 and 95 were drafted using data from Dragsed. The figures show dominant size fractions at each sampling station. These site-specific data indicate sand dominates Gaspé harbour areas and the Magdalen Islands region.

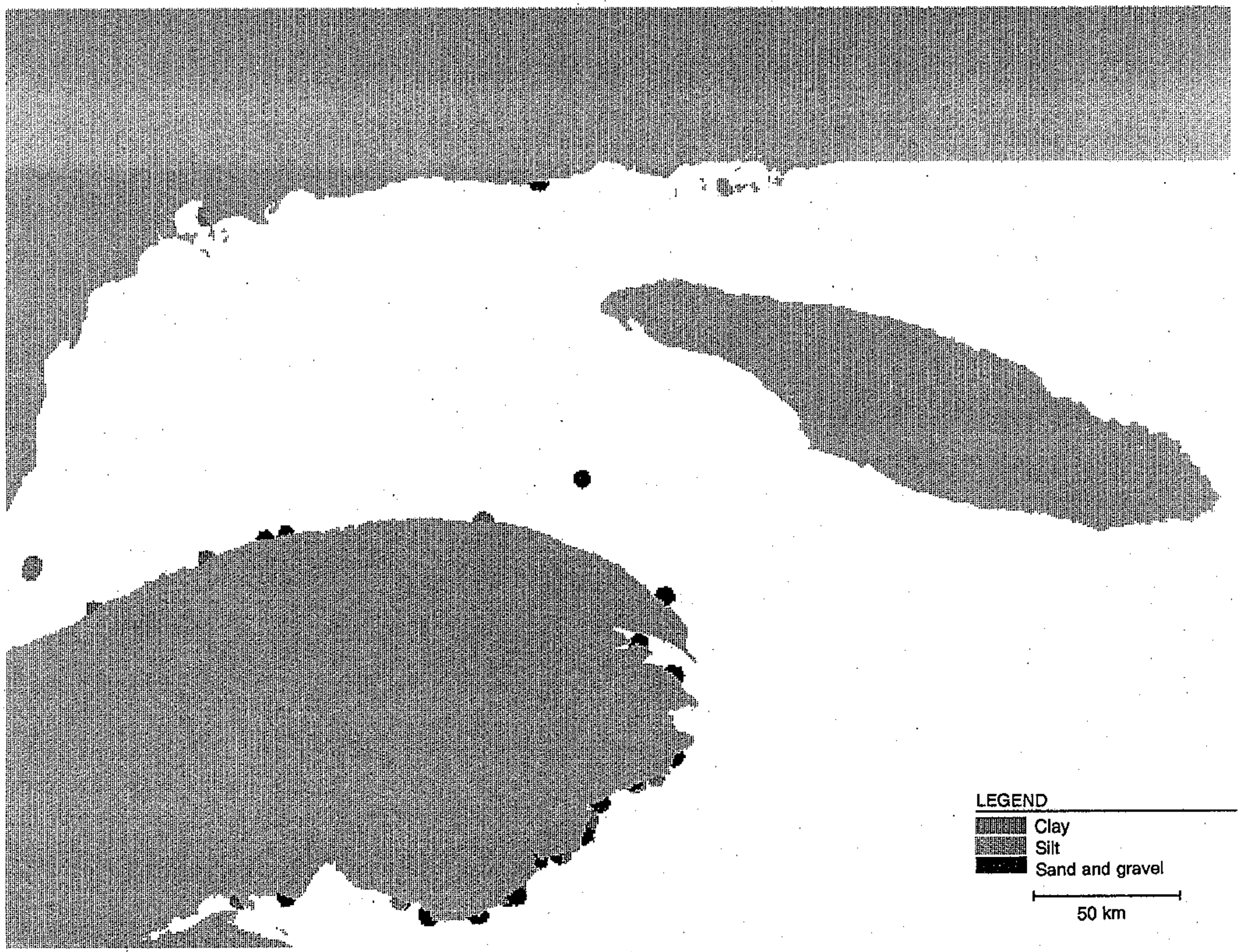


Figure 94 Dominant size fractions in the Gulf of St. Lawrence

Figure 95 ***Dominant size fractions in the Magdalen Islands***

8.1.4 Physical chemistry. Mercury levels are low in the Gulf of St. Lawrence (mean of 0.15 µg/g), approaching natural background levels. There is no clear pattern of mercury deposit nor any evidence that anthropogenic mercury has reached the gulf (Loring. 1975).

Loring (1978a, 1979) analyzed gulf sediment for five other trace metals. On average, gulf sediment proved only slightly enriched by chromium (Table 52); concentrations of the other metals were natural background levels. Greatest enrichment by copper, lead and zinc was detected in the fine sediment of the central troughs and of certain shelves. Most of the sandy shelves, apart from those north of Anticosti Island, are slightly contaminated by these three metals.

Table 52 Mean metal (Cr, Cu, Ni, Pb and Zn) concentrations and standard deviations in surface sediment in the Gulf of St. Lawrence (Loring 1978a, 1979)

Location	Cr (µg/g)	Cu (µg/g)	Ni (µg/g)	Pb (µg/g)	Zn (µg/g)
Gulf	87 ± 18.1	25 ± 9.6	36 ± 11.3	21 ± 5.5	84 ± 22

Gobeil (1991) confirms that trace metal concentrations in the Laurentian Trough (in the centre of the gulf) are close to natural background levels. Table 53 lists mean concentrations in surface sediment at one station.

As for spatial trends, total copper, zinc and to a lesser extent lead concentrations in the pelites decrease from the upper estuary seaward. The reverse is true of nickel. Chromium levels are higher in the lower estuary and the gulf than in the upper estuary and the Saguenay Fjord and exceed TET quality criterion in three spots.

Table 53 Sediment quality in the Laurentian Trough (Gulf of St. Lawrence) (after Gobeil, 1991)

Metal	Concentration (µg/g)	Sediment quality criteria (µg/g)		
		NET criterion	MET criterion	TET criterion
Lead	27	23	42	170
Cadmium	0.16	0.2	0.9	3
Mercury	0.07	0.05	0.2	1
Zinc	107	100	150	540

Cadmium levels are high in spots along the nearshore of the gulf: Chloridorme, Gaspé, Newport Point and East Port Daniel (Table 54). Nickel levels also exceed TET in places (Cap Chat, Gascons, Gaspé, Newton Point) as does mercury (Sept Îles) (figures 96 to 103).

Highest trace metal concentrations were detected at the Gaspé dock (Sandy Beach), where major contamination by cadmium, nickel, chromium, copper, lead and zinc was detected, probably associated with copper ore in the sediment as a result of transshipping. Potential sources of mercury at Sept Îles are municipal discharges and harbour, mining, industrial, marina and fishing activities. No potential sources clearly explain exceedences (low for the most part) at other municipalities.

In the Magdalen Islands, two metals were detected in high concentrations in specific spots: cadmium in the Havre Aubert (Amherst Island) harbour and chromium in the Fatima harbour. All other measured concentrations were either at or slightly above natural background (figures 104 to 111).

Table 54 Extremes recorded in nearshore sediment of the Gulf of St. Lawrence and the Magdalen Islands

Site	Year	Metal	TET criterion (µg/g)	Concen-tration (µg/g)
Cap Chat	87	Ni	61	81
Cloridorme	85	Cd	3	10.1
Gascons (Chapados Creek)	86 87	Ni Ni	61	72 86
Gaspé (Sandy Beach)	86	Cd Cr Cu Ni Pb Zn	3 100 86 61 170 540	35 143 14 457 111.4 14 700 3 570
Newport Point	88	Cd Ni	3 61	3.7 76
East Port Daniel	87	Cd	3	5
Sept Îles	87	Hg	1	5.7
Fatima	88	Cr	100	100.9
Havre Aubert (Amherst Island)	87	Cd	3	6

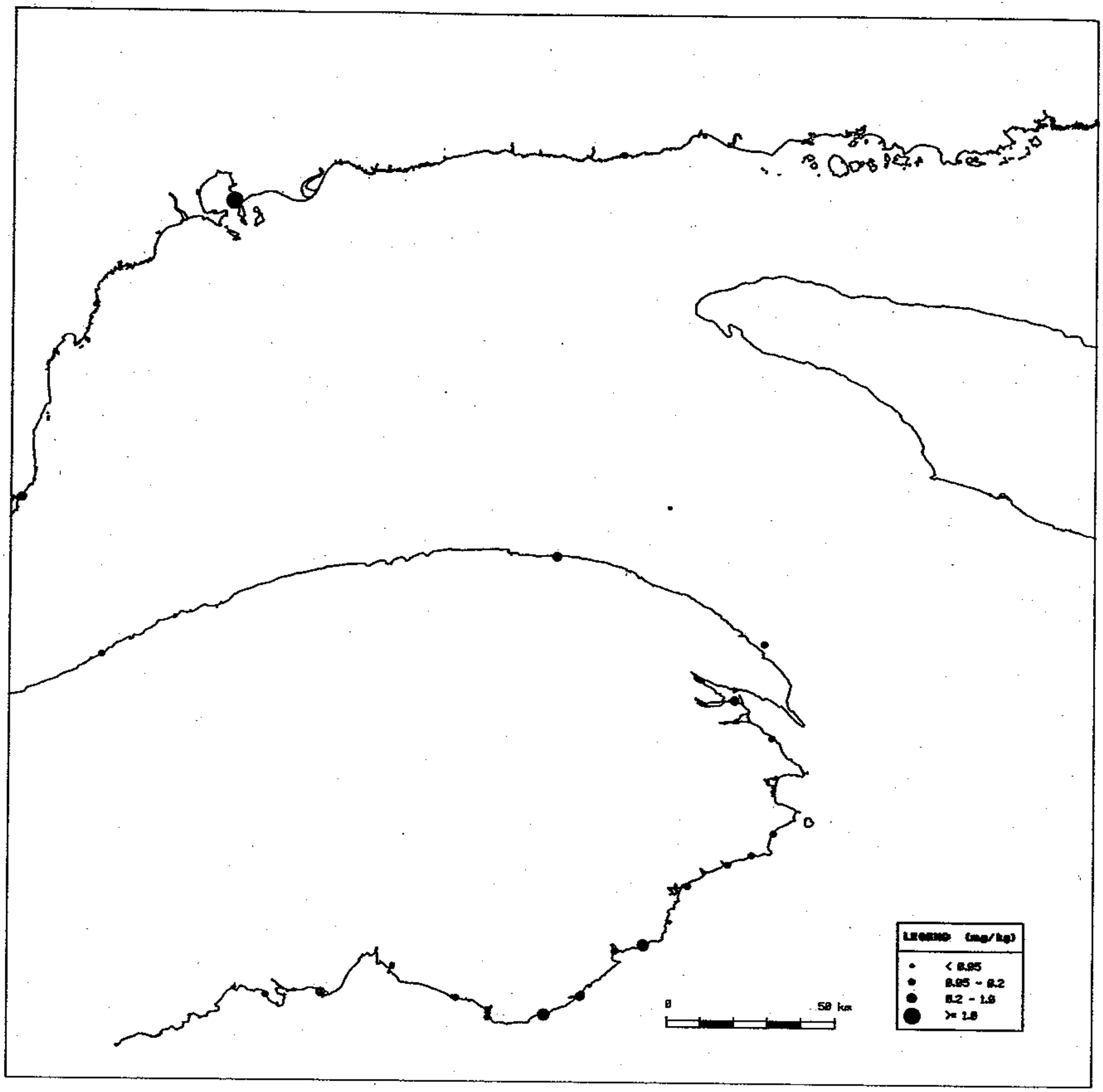


Figure 96 ***Mercury distribution in Gulf of St. Lawrence sediment (1985-1991)***

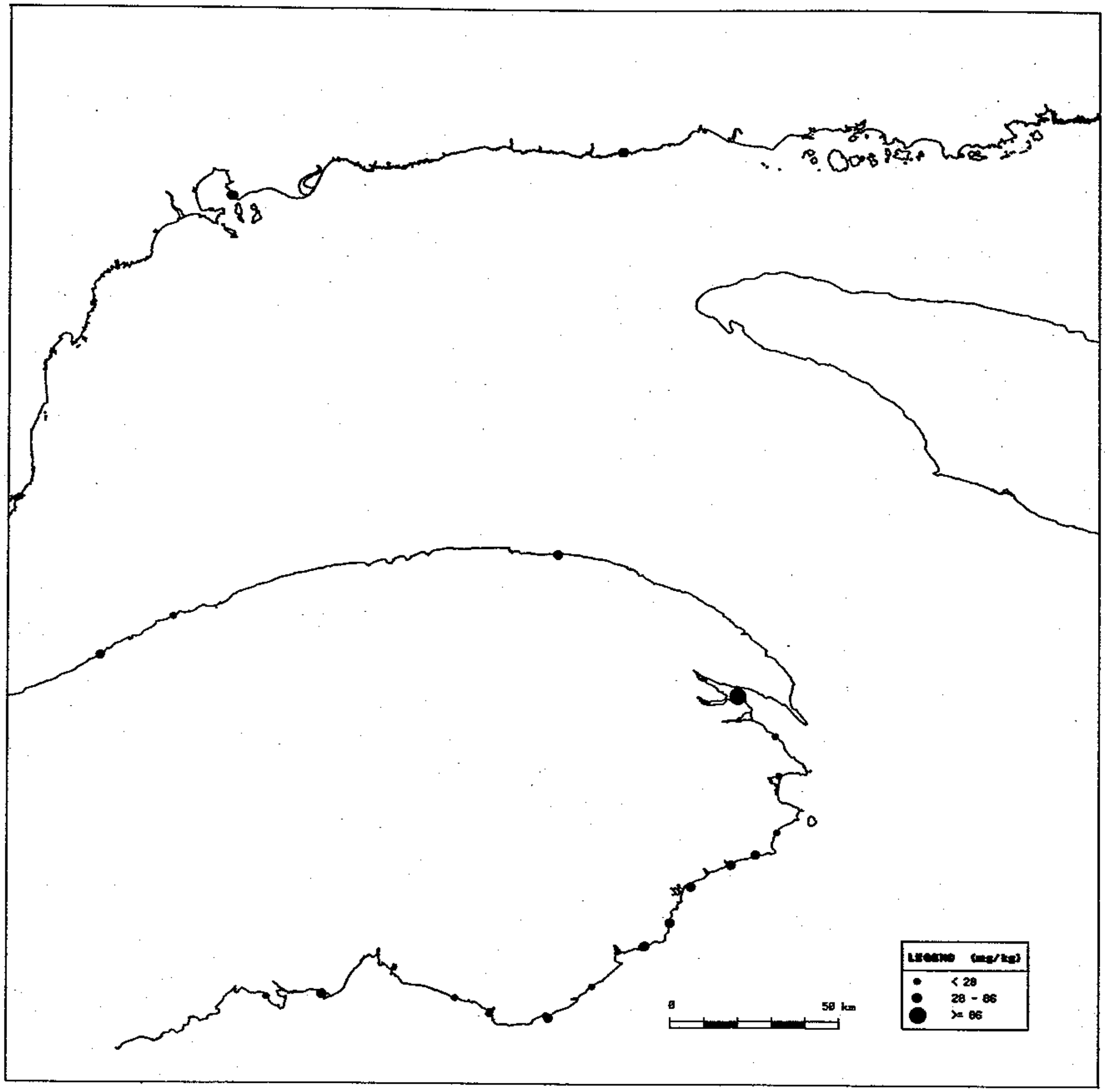


Figure 97 Copper distribution in Gulf of St. Lawrence sediment (1985-1991)

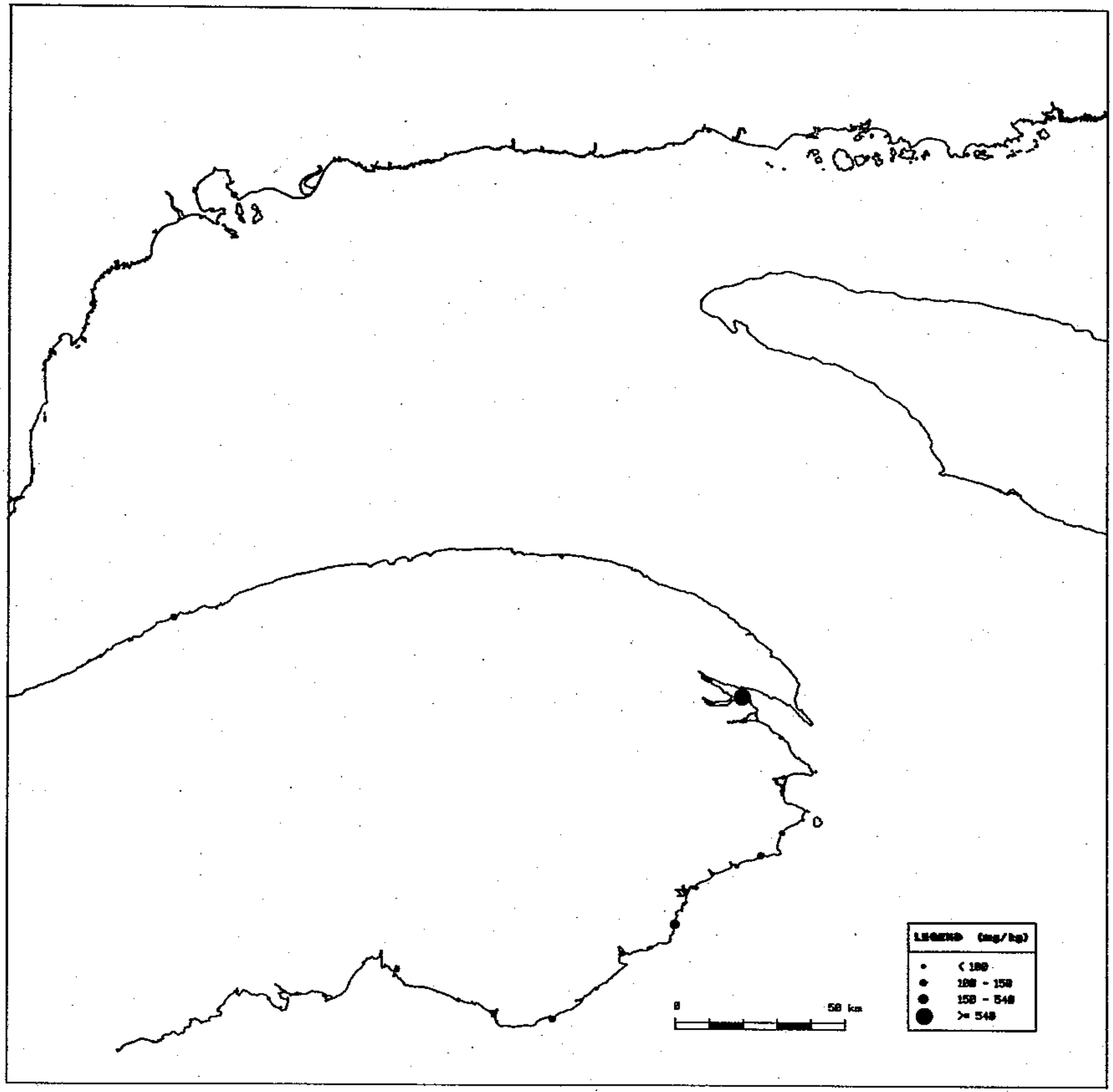


Figure 98 Zinc distribution in Gulf of St. Lawrence sediment (1985-1991)

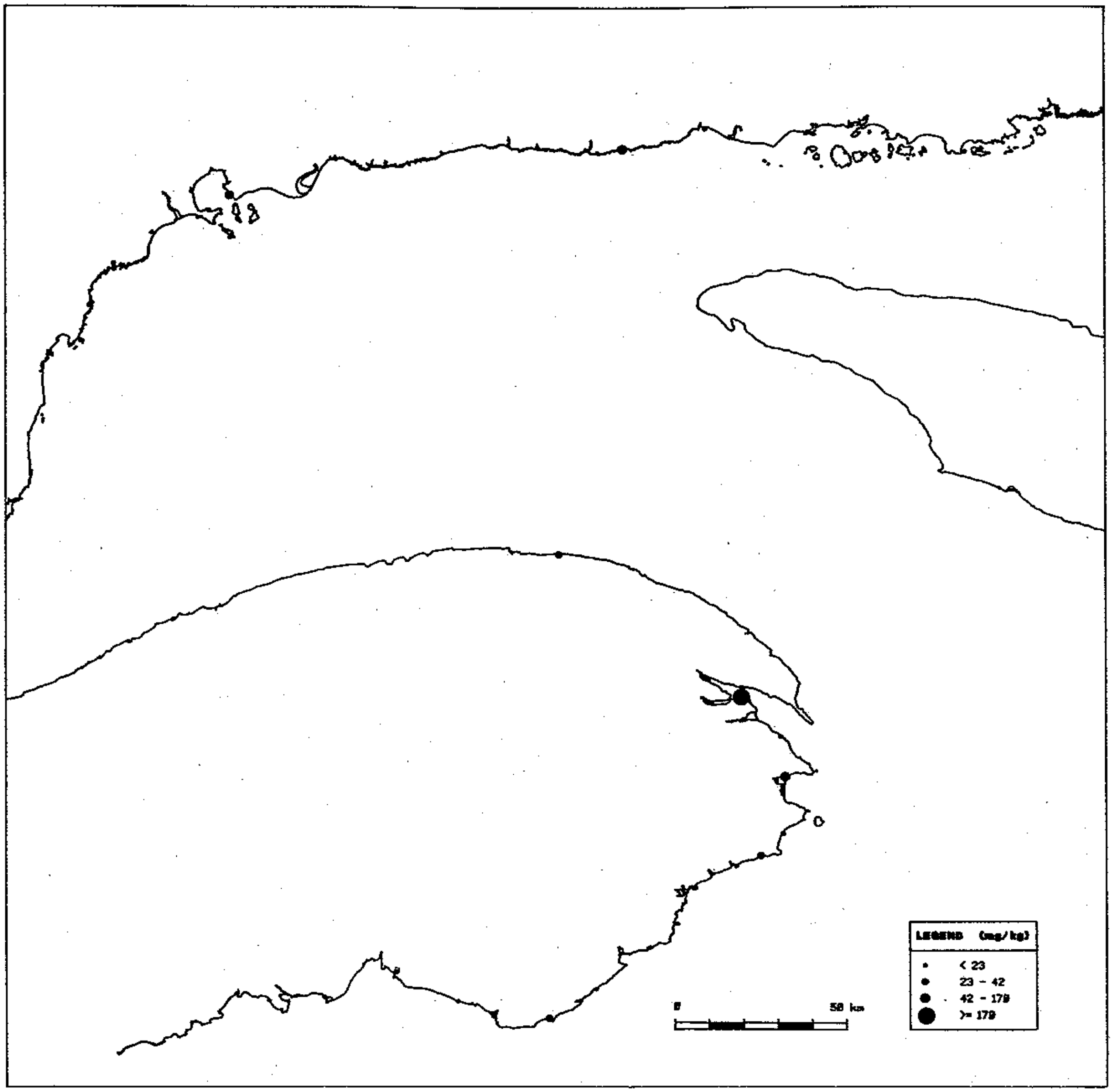


Figure 99 Lead distribution in Gulf of St. Lawrence sediment (1985-1991)

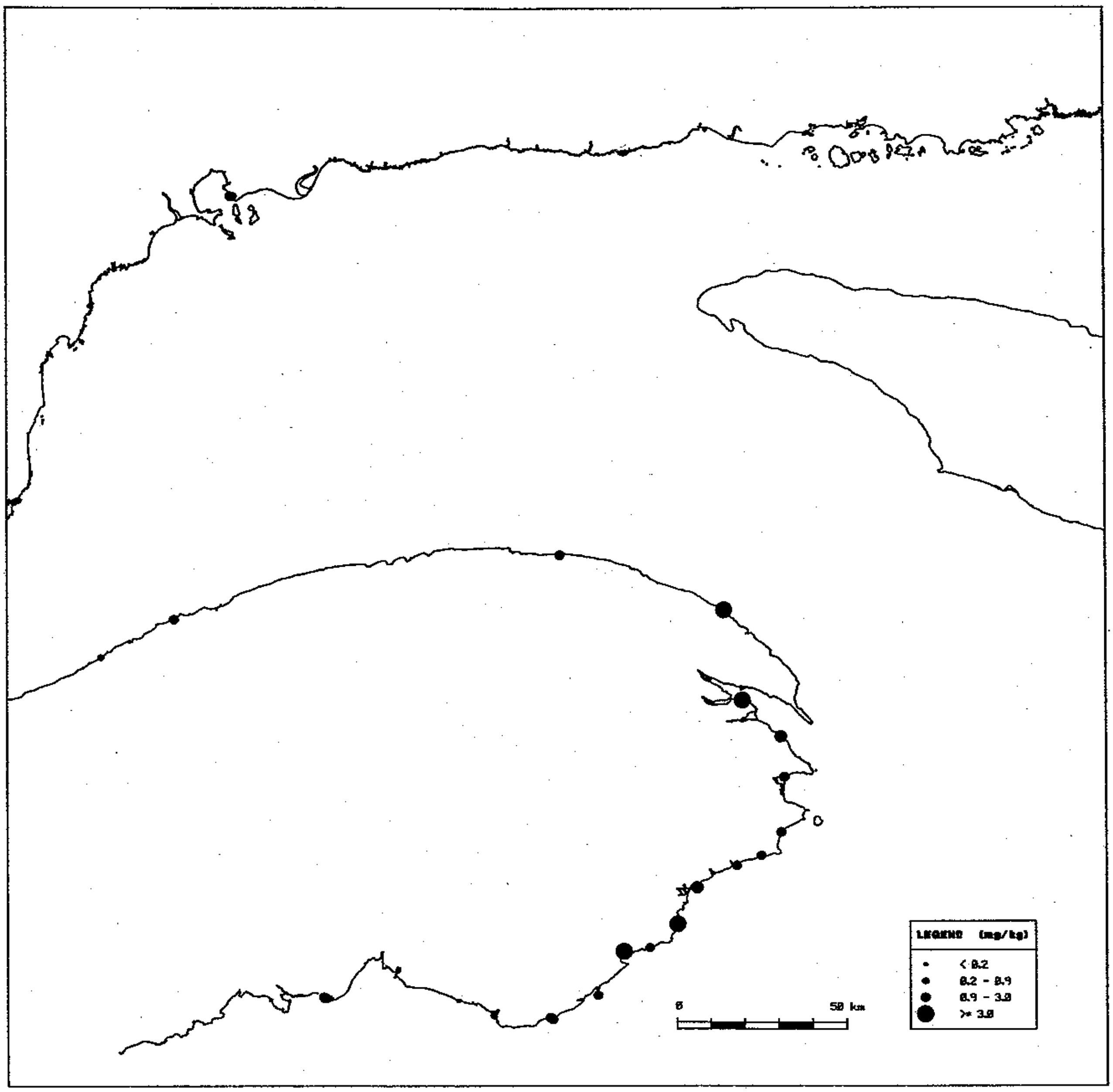


Figure 100 Cadmium distribution in Gulf of St. Lawrence sediment (1985-1991)

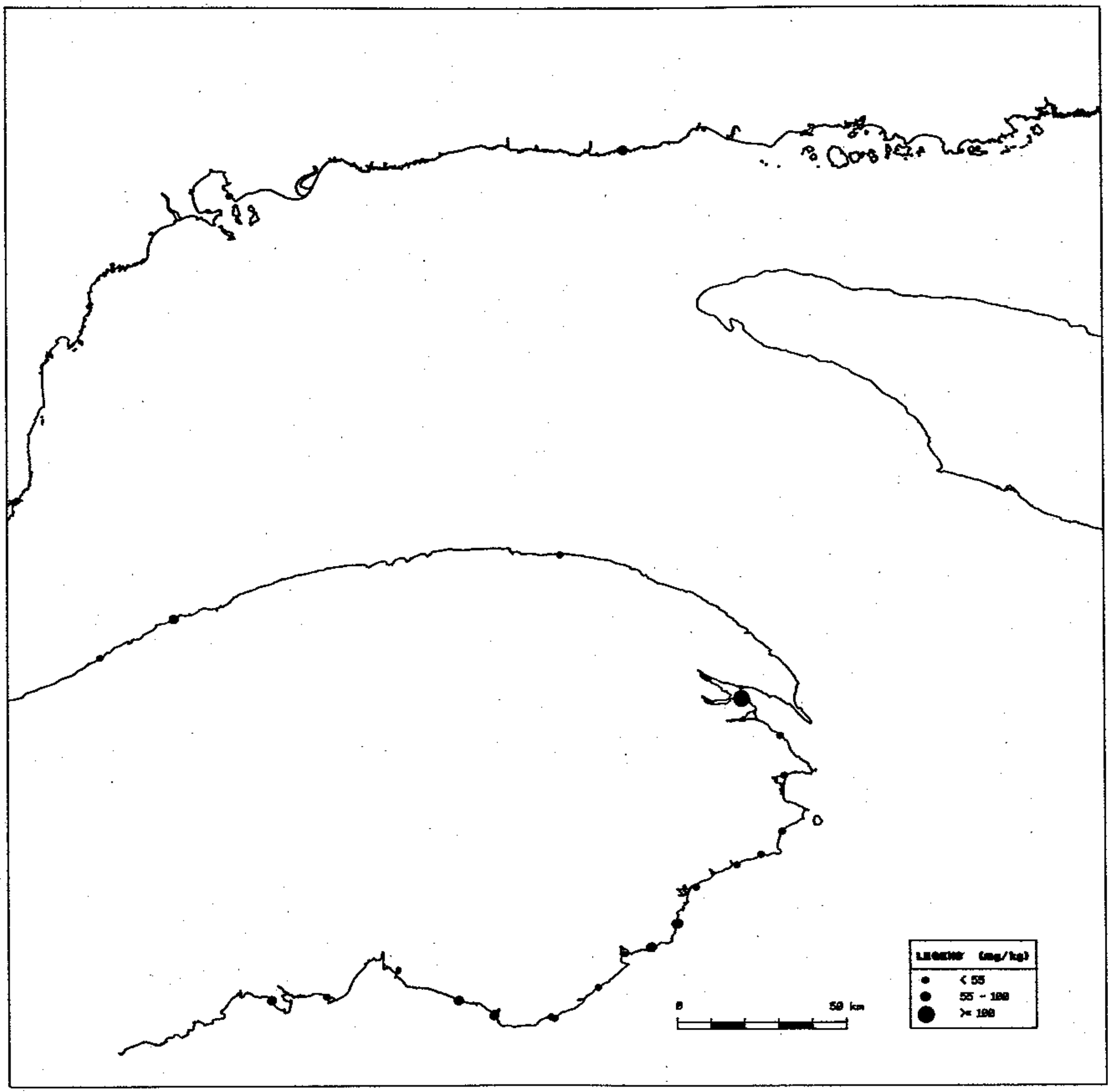


Figure 101 Chromium distribution in Gulf of St. Lawrence sediment (1985-1991)

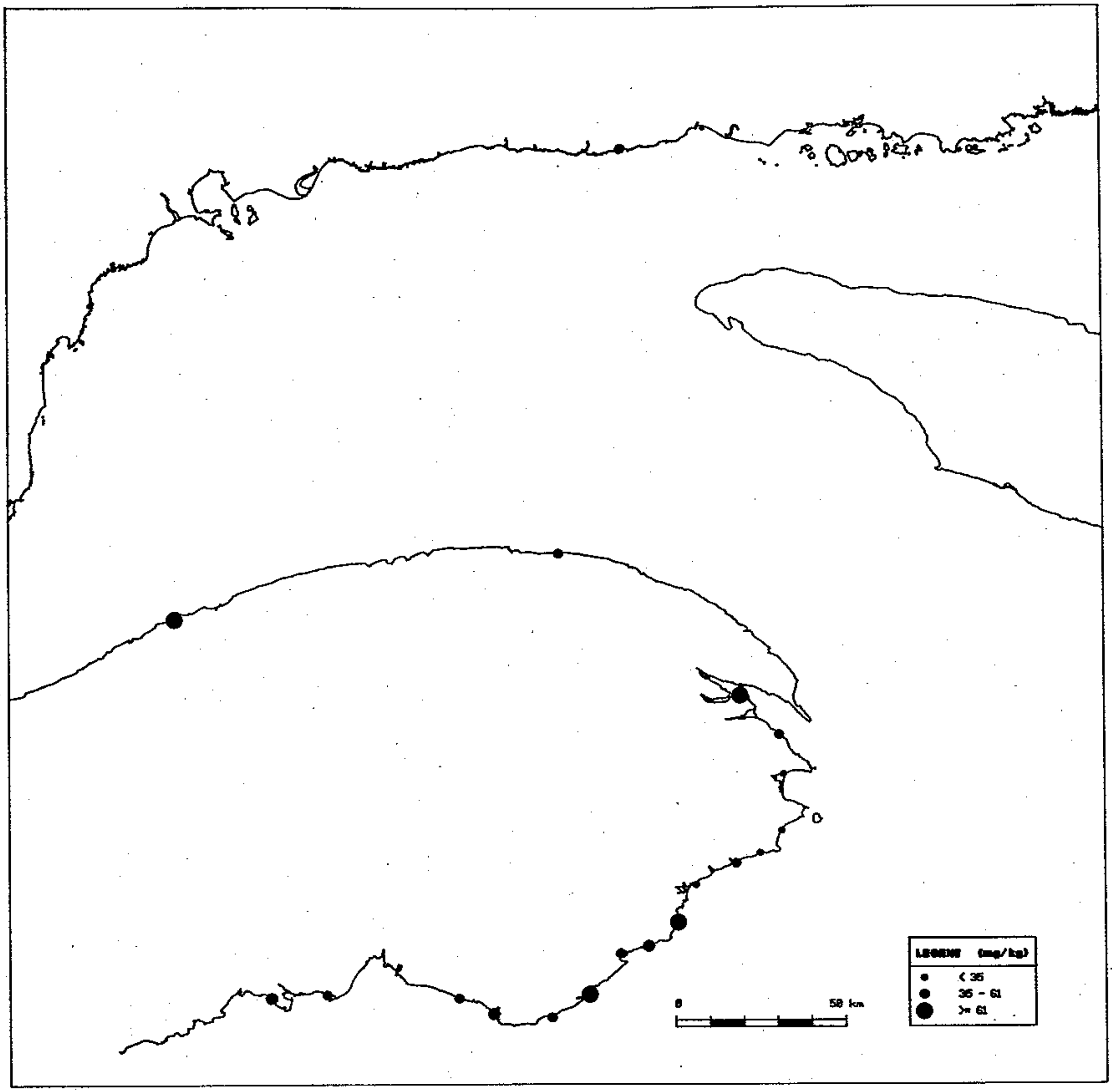


Figure 102 Nickel distribution in Gulf of St. Lawrence sediment (1985-1991)

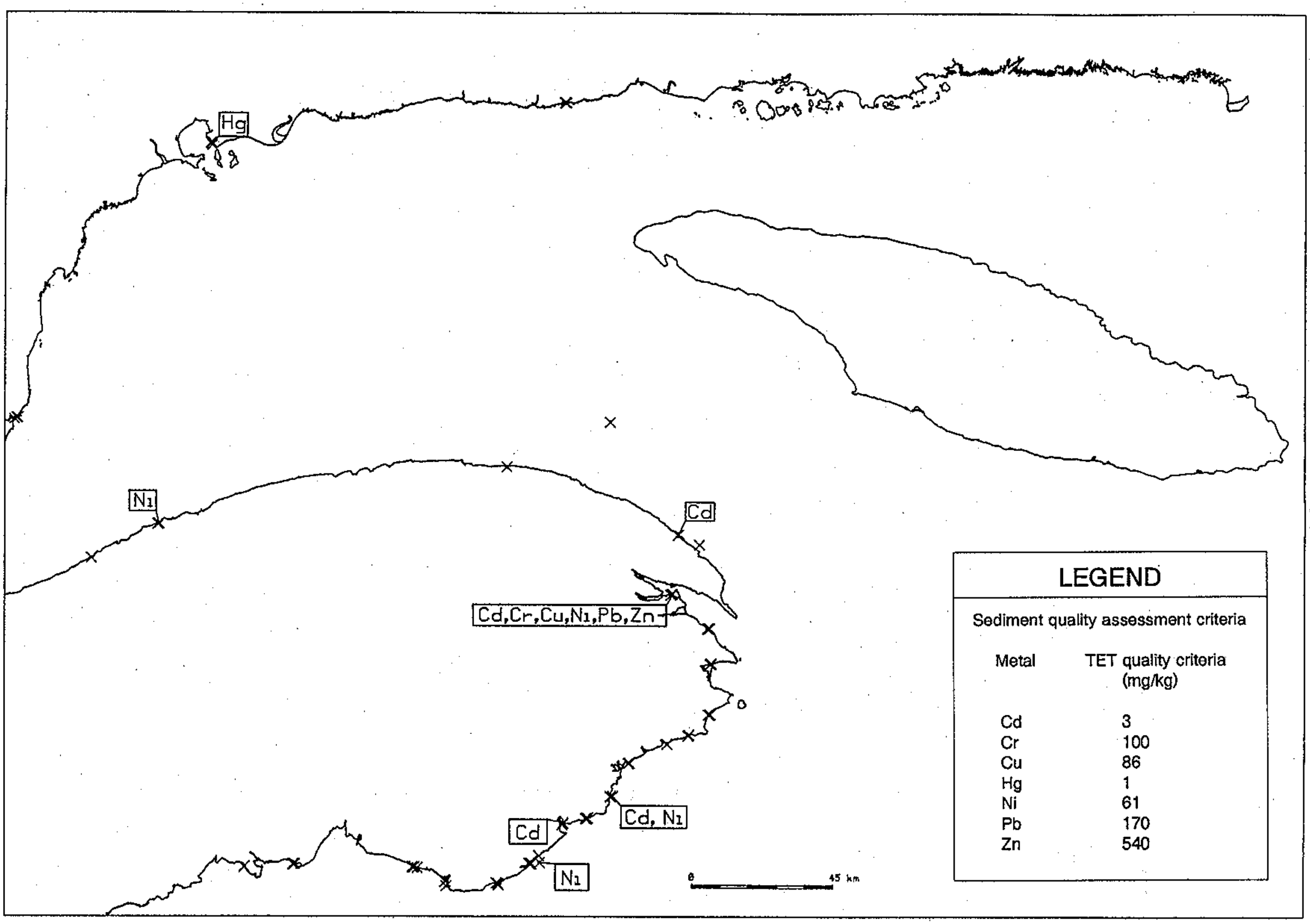


Figure 103   Exceedences of TET quality criteria in Gulf of St. Lawrence sediment (1985-1991)

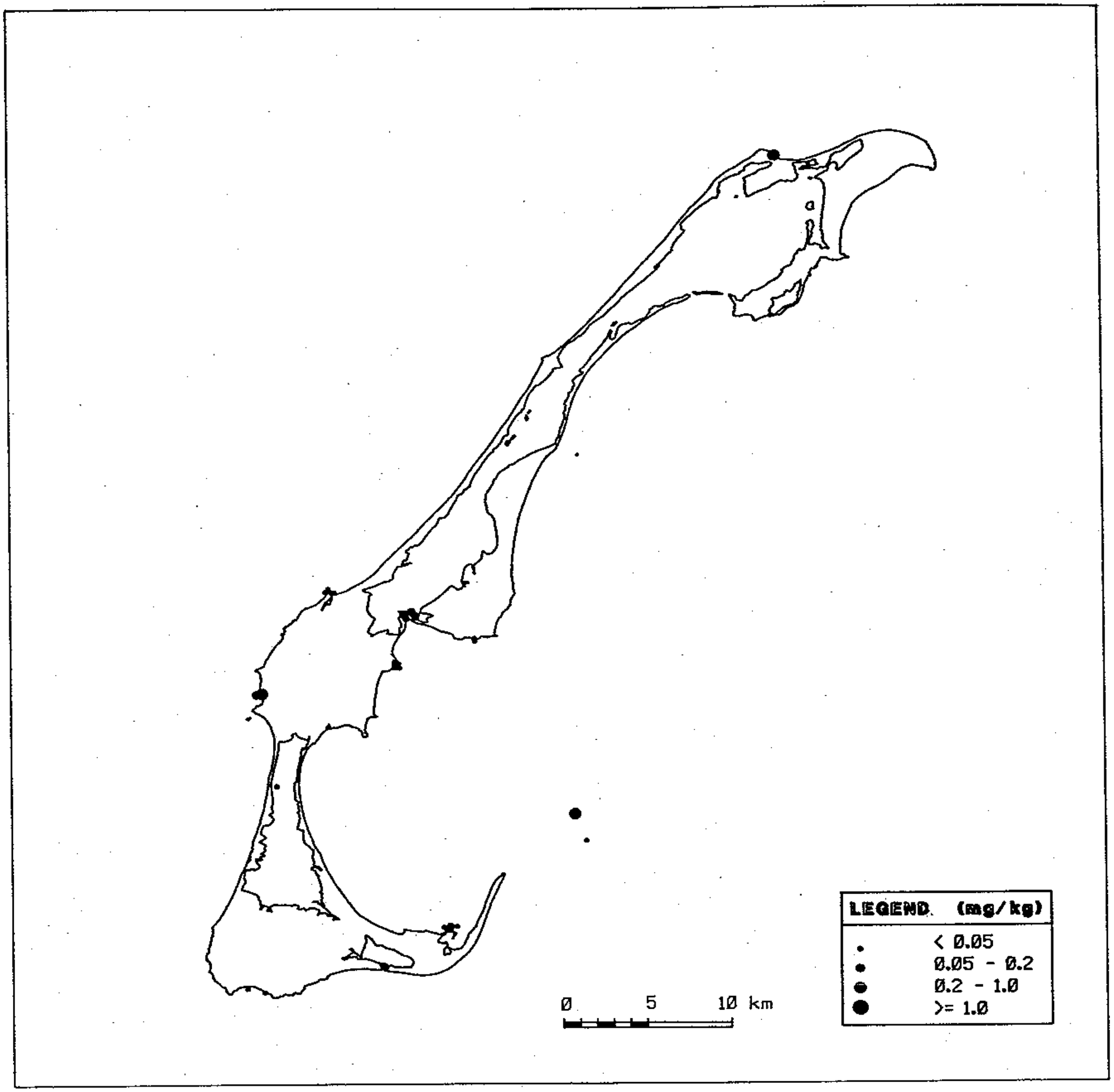


Figure 104 Mercury distribution in Magdalen Islands sediment (1985-1991)

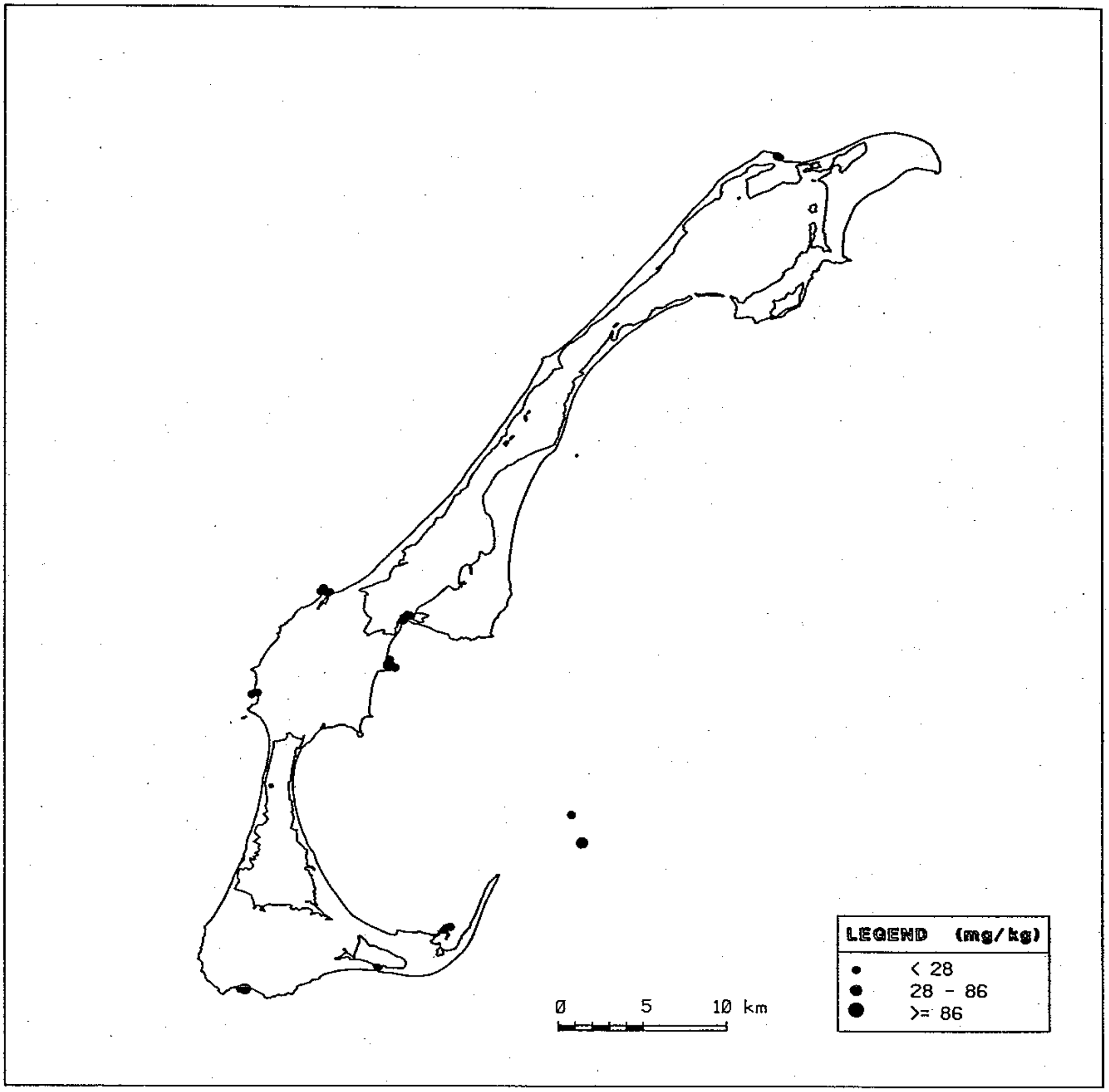


Figure 105 Copper distribution in Magdalen Islands sediment (1985-1991)

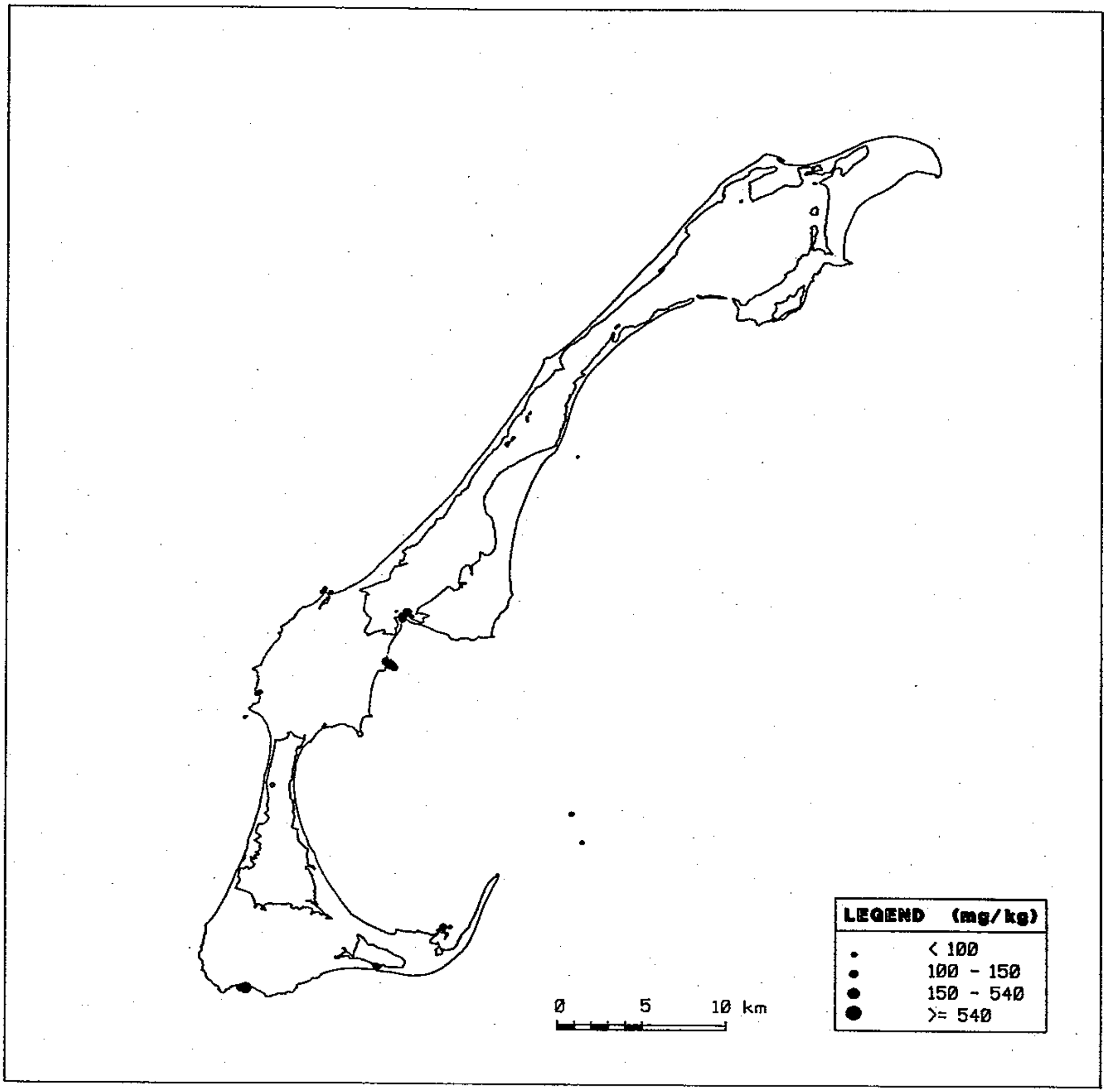


Figure 106 Zinc distribution in Magdalen Islands sediment (1985-1991)

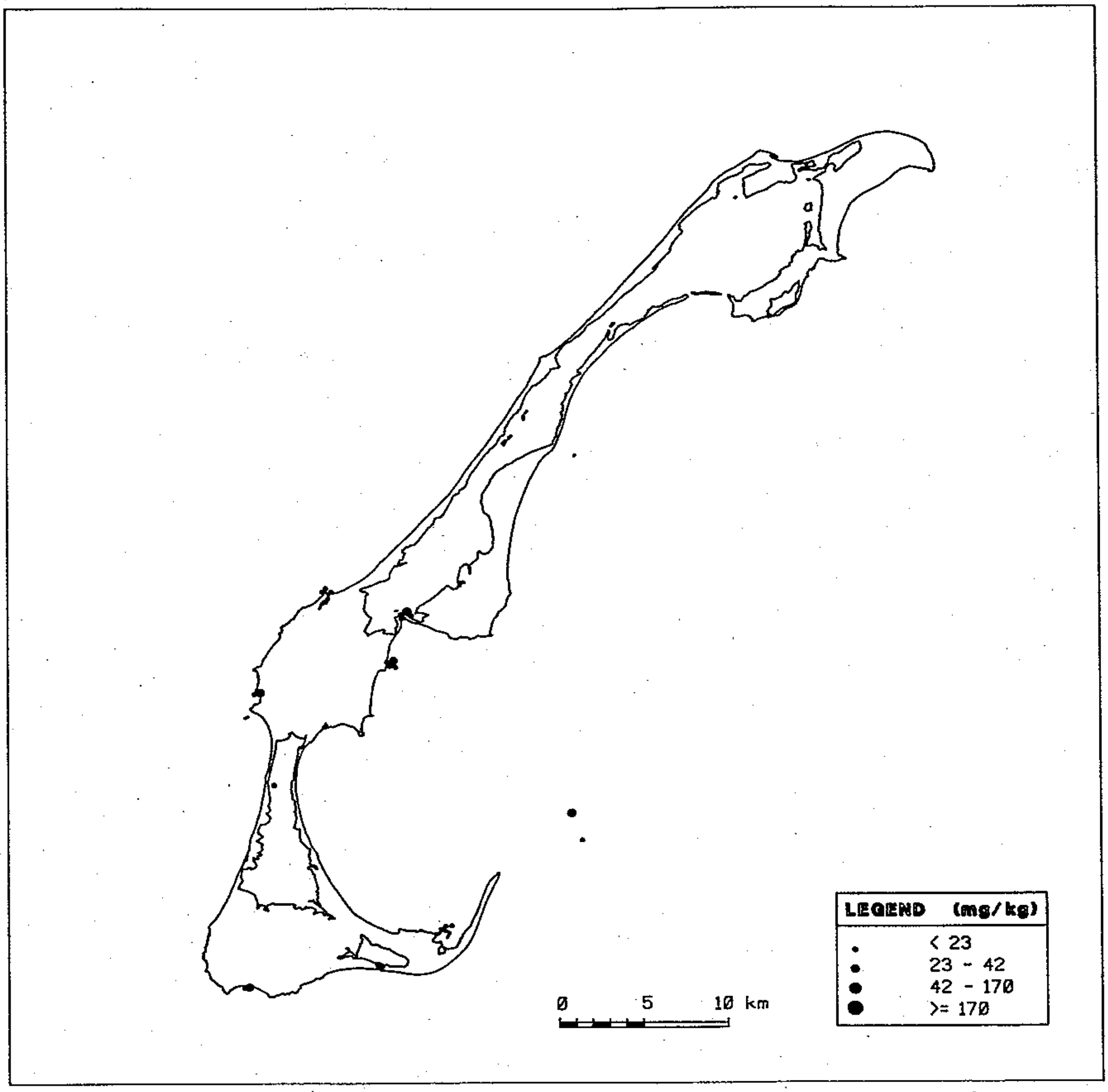


Figure 107 Lead distribution in Magdalen Islands sediment (1985-1991)

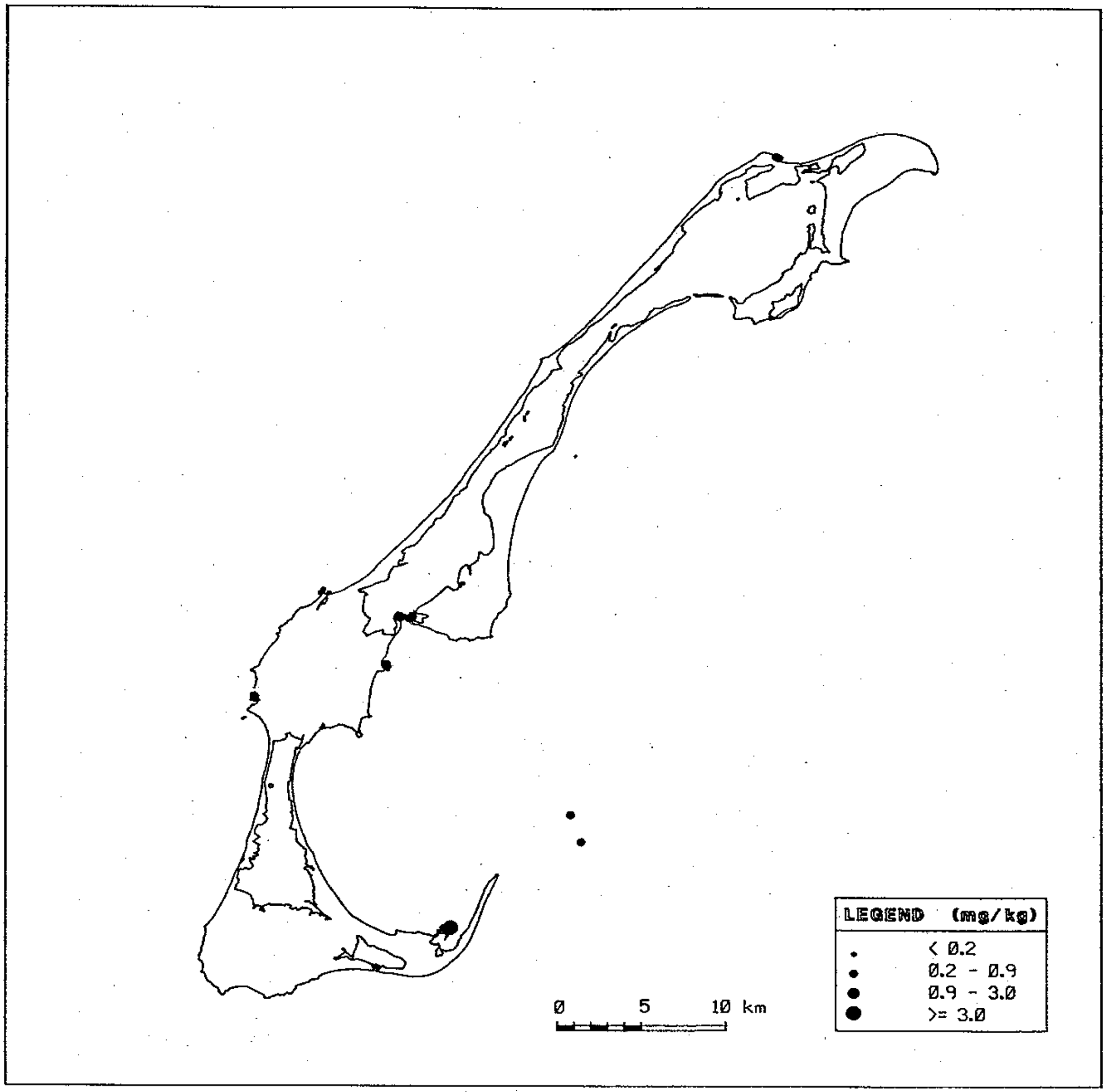


Figure 108 Cadmium distribution in Magdalen Islands sediment (1985-1991)

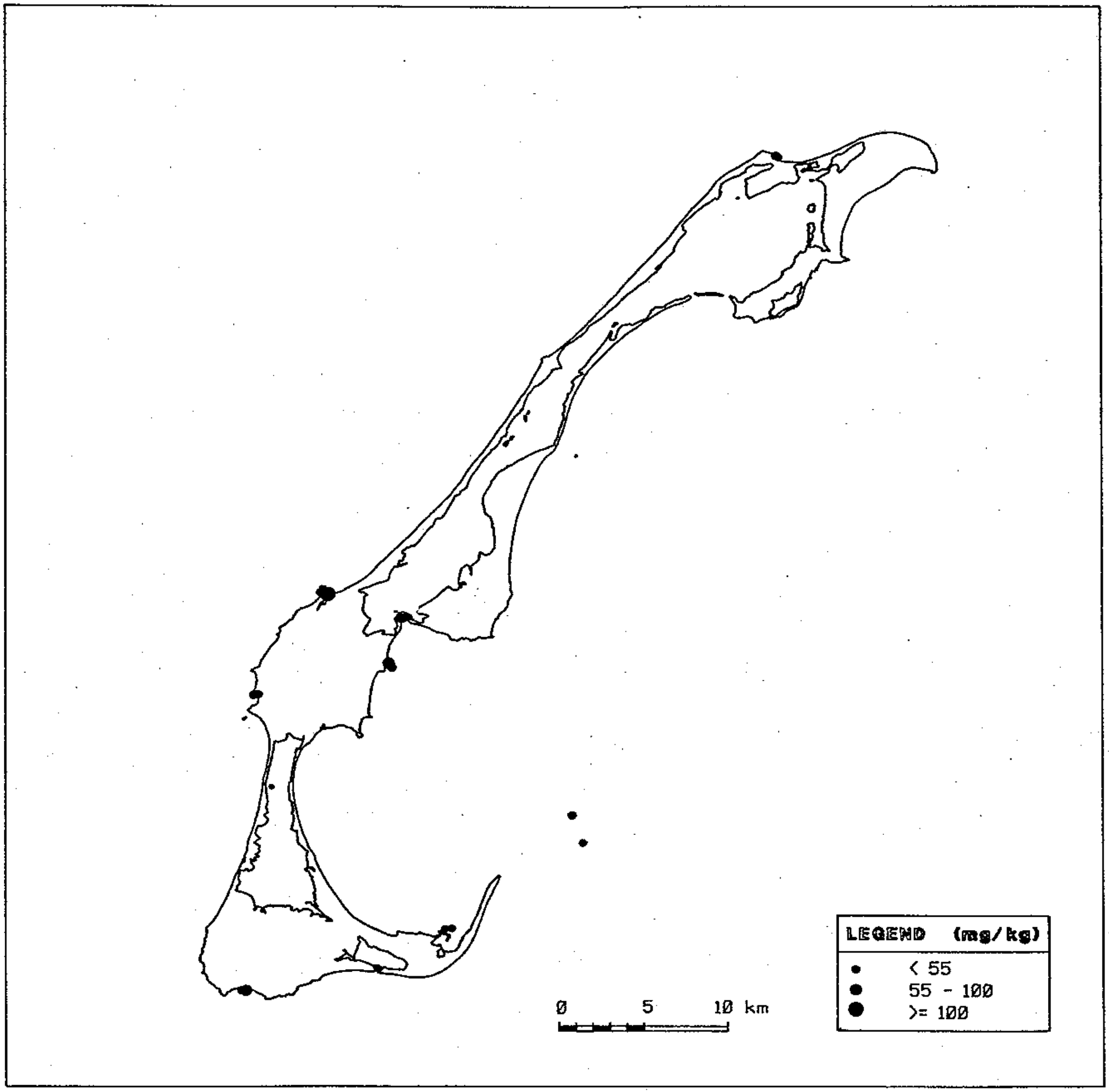


Figure 109 Chromium distribution in Magdalen Islands sediment (1985-1991)

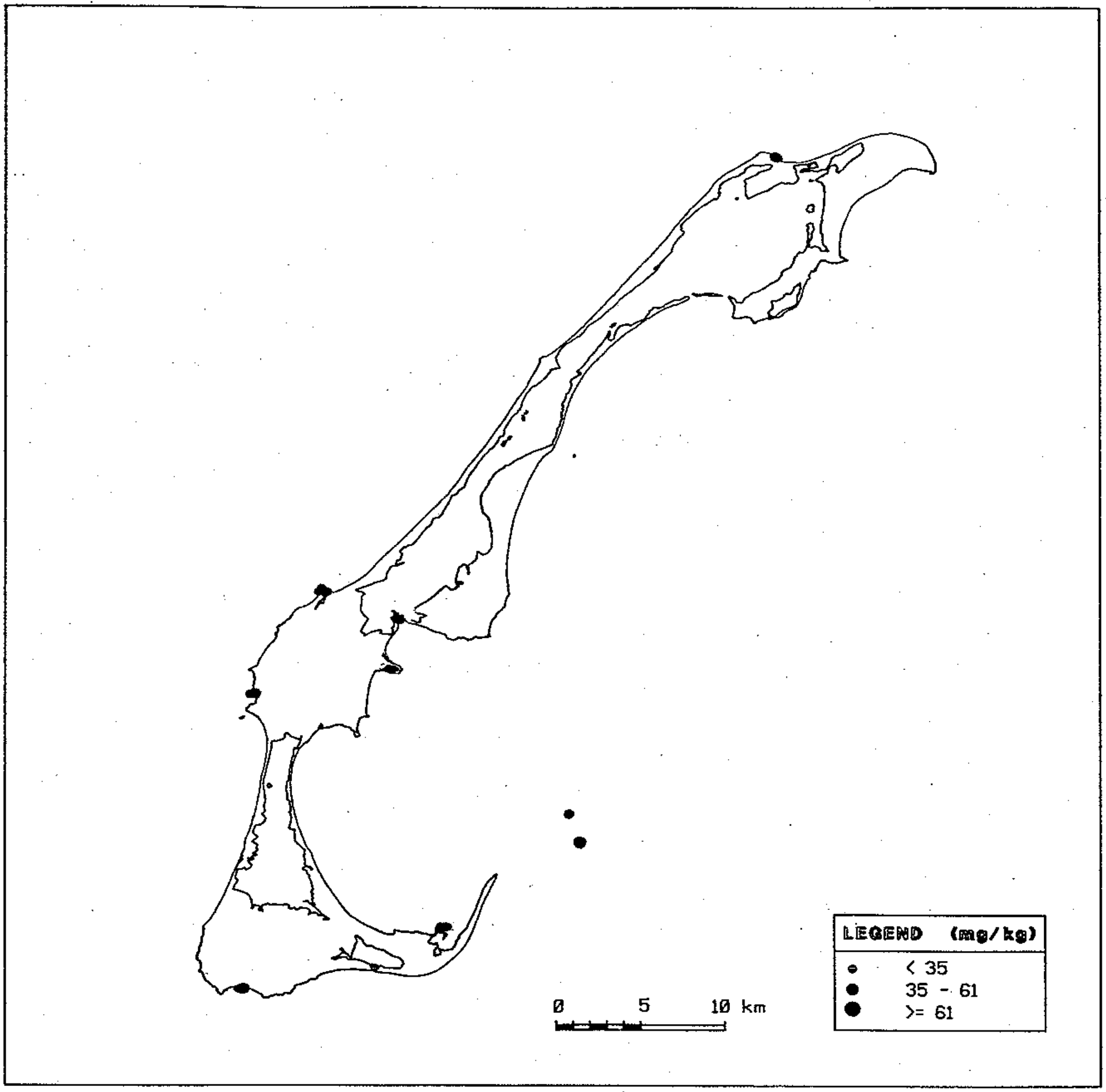


Figure 110 Nickel distribution in Magdalen Islands sediment (1985-1991)

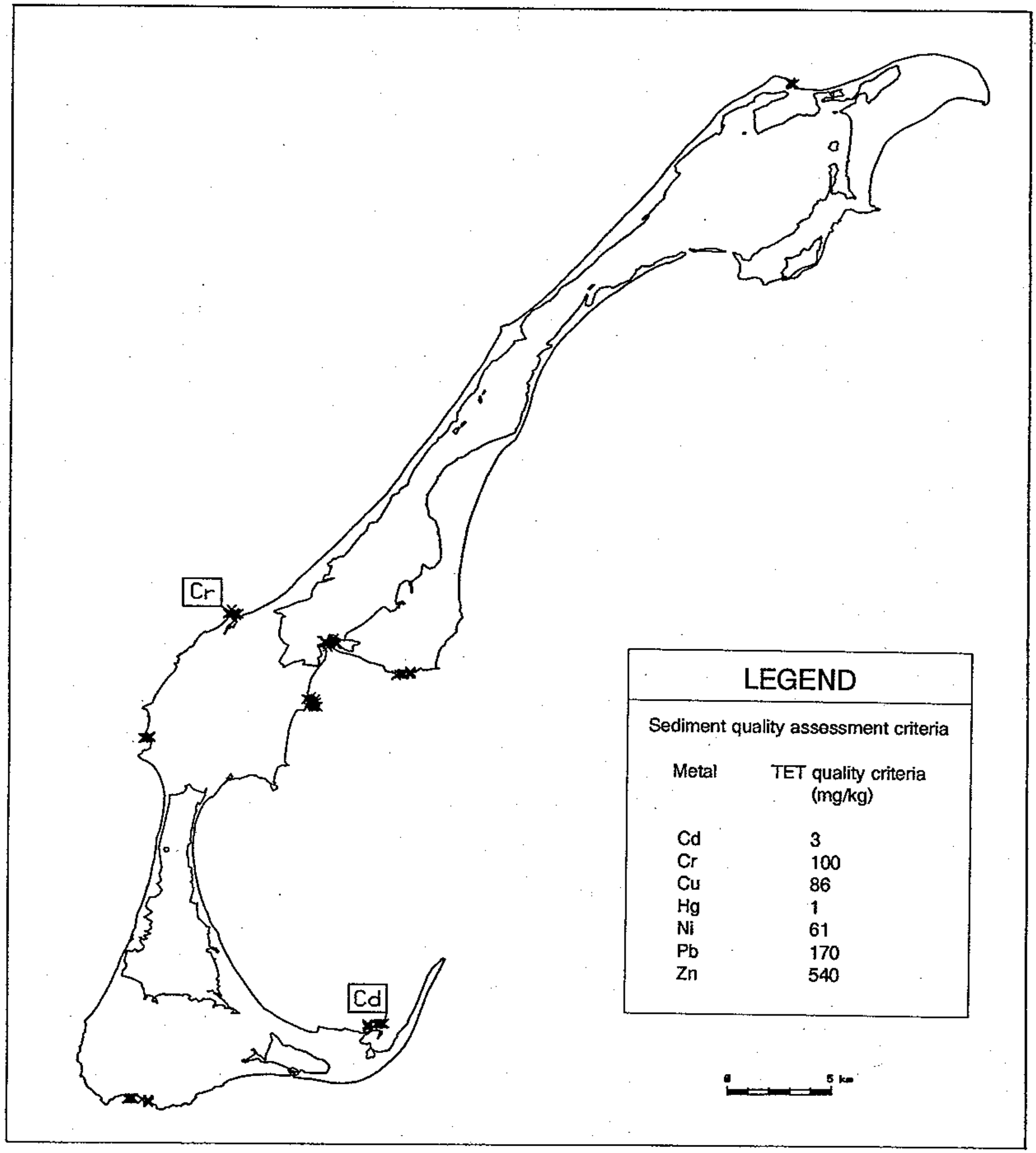


***Figure 111** Exceedences of TET quality criteria in Magdalen Islands sediment (1985-1991)*

The Québec portion of the St. Lawrence Seaway and the shipping channel was developed in stages between the end of the 19th century and the middle of the 20th century (Figure 112). The shipping channel is now 240 m wide and more than 10.5 m deep. Work is in progress to make the channel 11 m deep between Québec City and Montréal--not a large-scale project since most of the corridor is already that deep.

Parts of the shipping channel must be constantly maintained to guarantee required channel dimensions. In addition, sedimentation occurs at certain docks and marinas belonging to the federal government and frequent dredging is required. The Canadian Coast Guard is responsible for maintenance. Dredging is also performed sporadically by the Government of Québec (to maintain ferry docking areas), by municipalities (to create or maintain marinas) and by private corporations (generally to maintain private docks used for transshipping).

In all, some 5 500 000 m^3 of sediment were dredged between 1983 and 1991, about 617 000 m^3/a (Table 51). More dredging operations were performed in the Gaspé than anywhere else along the St. Lawrence River--266 of a total 507 projects (52 percent) (areas K and L, Figure 113). The Magdalen Islands came next, followed by the upper estuary, the riverine estuary and the Île d'Orléans area (85, 45, 32 and 30 dredging operations respectively between 1983 and 1991). In all other areas listed in Figure 113, fewer than 20 dredging operations were performed during the period.

There is no direct relation between frequency of dredging and volume of material dredged however. For example, 1 300 000 m^3 of sediment were removed during the 30 dredging operations in the Île d'Orléans area, an average 44 000 m^3 per dredging operation. This is the second highest average per dredging operation throughout the St. Lawrence River system, exceeded only by dredging operations at the mouth of the Richelieu River which average 46 000 m^3 per operation. The mouth of the Richelieu River was dredged only twice during the reference period however. The Gaspé ranks second for total volume of sediment removed (978 000 m^3), but last for average volume

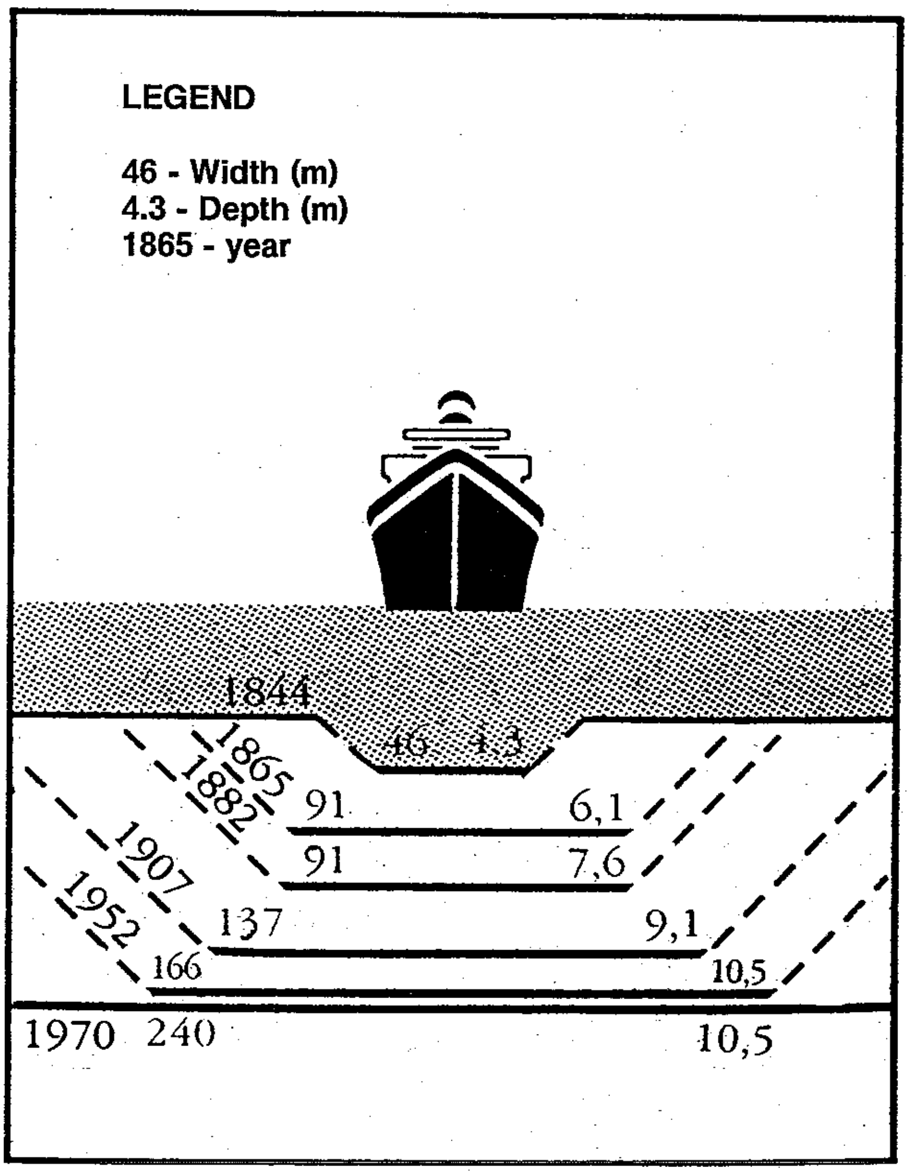


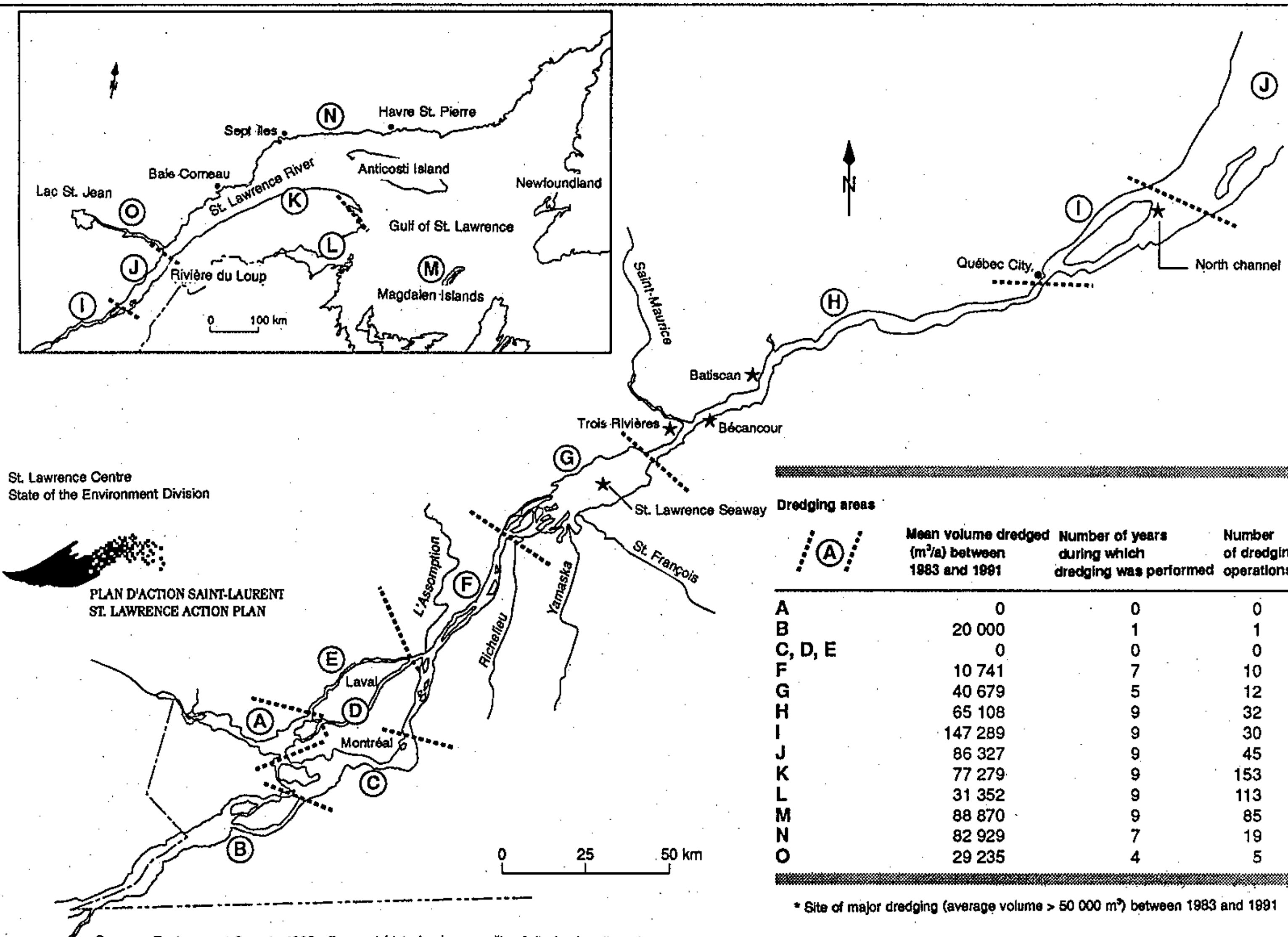
Figure 112 Shipping channel depth and width profiles since 1984 (Source: Canadian Coast Guard)

Table 55 Volume of material dredged between 1983 and 1991 (m^3)

Area	1983	1984	1985	1986	1987	1988	1989	1990	1991	TOTAL	No. of dredging operations	Average per operation	Average per year
A	0	0	0	00	0	0	0	0	0	0	0	0	0
B	0	0	0	19 600	0	0	0	0	20 000	20 000	1	20 000	20 000
C,D,E	0	0	0	0	0	0	0	0	0	0	0	0	0
F	9000	1 860	0	73 722	13 000	25 912	0	3 295	2 520	75 187	10	7 519	10 741
G	0	0	0	125 824	12 333	86 771	14 834	79 282	10 174	203 394	12	16 950	40 679
H	65 303	44 674	39 537	40 545	95 330	36 407	98 276	38 798	93 924	585 971	32	18 312	65 108
I	269 720	114 896	102 434	50 311	98 699	338 418	89 471	64 137	122 004	1 325 603	30	44 187	147 289
J	268 621	78 100	44 572	49 925	75 855	61 568	70 918	58 100	78 665	776 944	45	17 265	86 327
K	245 292	170 796	31 500	86 201	37 480	48 785	39 478	61 409	10 459	695 510	153	4 546	77 279
L	46 013	26 729	34 228	19 658	35 801	22 200	26 356	21 848	19 068	282 168	113	2 497	31 352
M	265 644	54 573	105 609	0	51 127	70 190	70 352	55 983	40 152	799 831	85	9 410	88 870
N	154 930	123 941	104 912	0	0	148 542	0	25 786	2 737	580 506	19	30 553	82 929
O	0	23 415	35 000	0	0	54 956	0	0	3 568	116 939	5	23 388	29 235
P	58 586	32 562	0	0	0	0	0	0	0	91 148	2	45 574	45 574
Total	1 383 109	671 546	497 792	465 786	419 625	893 749	409 685	408 638	403 271	5 553 201	507	10 953	617 022**
No. of dredging operations	77	67	57	57	51	64	49	48	37	507			
Average volume removed per operation	17 962	10 023	8 733	8 172	8 228	13 965	8 361	8 513	10 899	10 953			

* Only for years during which dredging was performed

** Number of years during which dredging was performed not considered



Dredging areas

A	Mean volume dredged (m^3/a) between 1983 and 1991	Number of years during which dredging was performed	Number of dredging operations
A	0	0	0
B	20 000	1	1
C, D, E	0	0	0
F	10 741	7	10
G	40 679	5	12
H	65 108	9	32
I	147 289	9	30
J	86 327	9	45
K	77 279	9	153
L	31 352	9	113
M	88 870	9	85
N	82 929	7	19
O	29 235	4	5

* Site of major dredging (average volume > 50 000 m^3) between 1983 and 1991

Dredging required to maintain the seaway and access channels and to build or maintain harbour facilities was considered when calculating volumes of dredged material.

Sources: Environment Canada 1993. Dragsed (data bank on quality of dredged sediment). St. Lawrence Centre. Technological Development Division.

Figure 113 Mean volume of sediment dredged (m^3) in the St. Lawrence River between 1983 and 1991

of material removed per dredging project (3675 m^3). The Magdalen Islands rank third for total volume of sediment removed (800 000 m^3); average volume removed per dredging operation was 9400 m^3, also low. The upper estuary comes next, with a total of 777 000 m^3 of sediment removed, or 17 000 m^3 per dredging operation. The riverine estuary and the north shore come last with 586 000 and 581 000 m^3 of sediment removed respectively. In all other areas listed in the figure, less than 250 000 m^3 of sediment were removed.

Clearly, dredging activities differ considerably from one region to the next. Close to Île d'Orléans, for example, dredging is infrequent, but more material is dredged from this area every year than from anywhere else along the St. Lawrence River. Dredging is frequent in the Gaspé and around the Magdalen Islands, but the amount of material removed during each operation is small. In Lake St. Pierre, the riverine estuary and the upper estuary, dredging is relatively infrequent but a moderate amount of material is removed each time. Dredging is infrequent at the mouths of the Richelieu and Saguenay rivers and along the north shore, but a lot of material is removed every time. Lake St. Francis, Lake St. Louis, Lake of Two Mountains, Rivière des Prairies and Rivière des Mille Iles are almost never dredged.

In parts of the St. Lawrence River, sedimentation is heavy and maintenance dredging is required annually or almost annually. Parts of the shipping channel that require frequent maintenance dredging are the bends of Lake St. Pierre, the Batiscan anchorage, the Bécancour bend, the Cap Santé channel, the Portneuf anchorage and the channel north of Île d'Orléans.

Five nearshore sites in the upper estuary, eighteen in the Gaspé and nine in the Magdalen Islands require very frequent maintenance dredging. Table 56 lists sites dredged regularly and volume of material removed annually.

The volume of material dredged annually is relatively constant and is generally about 430 000 m^3 if 1983 and 1988 are excluded (during these exceptional years 1 383 000 and 894 000 m^3 were removed, respectively). If the two years are included in the calculations, mean annual volume removed is 617 000 m^3.

Table 56 Sites dredged regularly and volume of material removed

	Area	Site	Volume dredged (m^3/a)
Shipping channel	G	Lake St. Pierre	35 002
	H	Batiscan (anchorage)	52 063
		Bécancour (bend)	17 922
		Cap Santé (channel)	9 635
		Portneuf (anchorage)	9 473
	I	North channel (Île d'Orléans)	90 280
Riverside communities	I	St. François (Île d'Orléans)	6 751
	J	Île aux Coudres	7 371
		Île aux Grues	6 819
		Rivière du Loup	45 120
		St. Joseph de la Rive	2 392
	K	Anse au Griffon	2 759
		Cap des Rosiers	1 493
		Grande Vallée	1 940
		Marsoui	1 875
		Petite Vallée	1 421
		Rimouski	41 054
		Rivière au Renard	1 755
		Rivière à Claude	1 875
		Ste. Marthe de Gaspé	1 438
	L	Anse à Beaufils	4 205
		Anse à Brillant	2 427
		Bonaventure	3 479
		Carleton	1 304
		Gascons (Anse à la Barbe)	1 264
		Gascons (Ruisseau Chapados)	1 516
		Port Daniel	3 162
		Leblanc creek	4 862
		St. Godefroi	1 887
	M	Étang du Nord	4 779
		Grosse Île	7 879
		Havre Aubert (Amherst Island)	4 823
		Havre aux Maisons	6 821
		Île d'Entrée	2 527
		Millerand	24 080
		Old Harry	1 163
		Pointe Basse	12 320
		Pointe aux Loups	631

* Sites dredged at least five times during the reference period.

10 CONCLUSION

The sediment quality analysis described in this report made it possible to identify spatial and temporal trends in surface sediment contamination in the St. Lawrence River between 1976 and 1989. Sites with highest concentrations of heavy metals were identified, and (whenever data were available) the high concentrations were related to toxic input from targeted industrial plants, tributaries, riverside municipalities and the international section of the river.

Particle-size distribution data were also reviewed and main sedimentation and erosion areas identified using available hydrodynamic and sedimentologic data and studies.

Dredging activities along the St. Lawrence River were reviewed to determine scope of dredging activities over time and at specific sites, susceptibility to sedimentation of private and public harbours, and areas of the seaway and shipping channel conducive to sedimentation.

Spatial coverage of the samples used for analysis ranged from good to passable. There are insufficient recent data on sediment between Lake St. Francis and Lake St. Louis (in the Beauharnois Canal, the international section of the St. Lawrence and the St. Charles River), in the Montréal-Sorel corridor and in the southern part of Lake St. Pierre. A special sampling effort must be made if sediment quality in these areas is to be adequately assessed.

Since only extractable portions of heavy metals can enter the food chain, it is recommended, in compliance with the *Methods Manual for Sediment Characterization* (St. Lawrence Centre, 1992), that extractable fraction analysis be given preference over total fraction analysis in the future.[6]

Monitoring of sediment quality in the St. Lawrence River shows surface sediment quality has improved; contamination by seven metals (cadmium, chromium,

---

6. The extractable portion comprises only the four bioavailable fractions: the exchangeable fraction, the fraction bound to carbonates, the fraction bound to iron and manganese hydroxides and the oxidizable fraction (the fraction bound to sulphides and organic matter).

copper, mercury, nickel, lead and zinc) decreased where sources of contamination were checked. Although the mechanisms governing the improvement are not well understood, the improvement should nevertheless be taken into account when setting priorities for aquatic environment restoration projects.

Dredging activities that entail removing large volumes of contaminated sediment have a major negative impact on the aquatic environment, and this too must be taken into consideration. Such activities release contaminants in the anoxic layer of sediment that would have remained trapped in the sediment had there been no change in their physicochemical environment.

BIBLIOGRAPHY

Allen, R.J. 1986. The limnological units of the lower Great Lakes - St. Lawrence corridor and their role in the source and aquatic fate of toxic contaminants. *Water Poll. Res. Journal Canada* 21 (2): 168-186.

Anderson, J. and H. Biberhofer. 1988. *Water and Suspended Sediment Quality in the St. Lawrence River at Cornwall/Massena.* St. Lawrence River Remedial Action Plan Data Report. 14 p.

Anonymous (1982). *Toxic Substances Control Programs in the Great Lakes Basin.* Report prepared for the Great Lakes Water Quality Board, International Joint Commission, 94 p.

Argus. 1991. *L'érosion des îles du Saint-Laurent tronçon Montréal - lac Saint-Pierre.* Report prepared for Environment Canada and the Canadian Coast Gurad.

Asseau. 1992a. *Bilan des apports toxiques et inventaire des usages du fleuve Saint-Laurent. Vol. 1 - Secteur Cornwall à Beauharnois. ZIP 1, 2, 3 et 4. Rapport d'étude.* Prepared with INRS-Eau for the St. Lawrence Centre, Environment Canada.

Asseau. 1992b. *Bilan des apports toxiques et inventaire des usages du fleuve Saint-Laurent. Vol. 2 - Secteur Beauharnois - Lanoraie. ZIP 5, 6, 7, 8, 9 et 10. Rapport d'étude.* Prepared with INRS-Eau for the St. Lawrence Centre, Environment Canada.

Asseau. 1992c. *Bilan des apports toxiques et inventaire des usages du fleuve Saint-Laurent. Vol. 3 - Secteur Lac Saint-Pierre. ZIP 11. Rapport d'étude.* Prepared with INRS-Eau for the St. Lawrence Centre, Environment Canada.

Asseau. 1992d. *Bilan des apports toxiques et inventaire des usages du fleuve Saint-Laurent. Vol. 4 - Secteur Trois-Rivières à Québec. ZIP 12, 13 et 14. Rapport d'étude.* Prepared with INRS-Eau for the St. Lawrence Centre, Environment Canada.

Barbeau, C., R. Bougie and J.E. Coté. 1981. Temporal and spatial variations of mercury, lead, zinc and copper in sediments of the Saguenay fjord. *Can. J. Earth Sc.,* 18: 1065-1074.

Brook, E.J. and J.N. Moore. 1988. Particle-size and chemical control of As, Cd, Cu, Fe, Mn, Ni, Pb, and Zn in bed sediment from the Clark Fork River. *Montana Sci. Tot. Environ.* 76: 247-266.

Caillé, A., P.G. Campbell, D. Cluis, D. Couillard, M. Pedneault, L. Potvin, A. Rousseau, J.L. Sasseville and A. Tessier. 1974. *Étude du fleuve Saint-Laurent: tronçon Cornwall-Varennes. Rapport scientifique No 41,* Institut National de la Recherche Scientifique (INRS-Eau), Sainte-Foy, Québec.

Carignan, R. 1989. *Étude préliminaire sur l'utilisation des radio-isotopes et autres marqueurs chronologiques pour déterminer la dynamique et le temps de résidence des sédiments du lac Saint-François.* Report prepared for the St. Lawrence Centre, Environment Canada.

Carignan S. and H.H.D. Alves. 1978. *Contaminants de l'environnement dans la zone d'influence industrielle de la rivière Saint-Louis dans la région de Beauharnois.* Fisheries and Environment Canada, Report EPS-8-QR-78-1.

CCREM. 1987. *Canadian Water Quality Guidelines.* Canadian Council of Resources and Environment Ministers.

Centreau. 1973. *Aspects physiques et sédimentologiques entre Cornwall et Varennes.* Centre de recherches sur l'eau, Université Laval. Report prepared for the St. Lawrence River Study Committee, 138 p. plus appendixes.

Centreau. 1974. *Aspects physiques et sédimentologiques entre Varennes et Montmagny.* Centre de recherche sur l'eau, Université Laval. Report prepared for the St. Lawrence River Study Committee, 266 p. plus appendixes.

Centreau. 1975. *Étude de la qualité des sédiments en suspension entre Québec et Trois-Pistoles.* Centre de recherche sur l'eau, Université Laval. Report prepared for the St. Lawrence River Study Committee, 154 p. plus appendixes.

Champoux, L. and H. Sloterdijk. 1988. *Étude de la qualité des sédiments du lac Saint-Louis 1984-1985. Rapport technique No 1. Géochimie et contamination.* Inland Waters Directorate, Environment Canada, 177 p.

Chan, C.H. 1980. *St. Lawrence River Water Quality Surveys, 1977.* Scientific Series No. 113, Inland Waters Directorate, Environment Canada, Ontario Region, 16 p.

Cluis, D., D. Couillard, R. Lapointe, L. Potvin, A. Rousseau, J.L. Sasseville and A. Tessier. 1975. *Étude du fleuve Saint-Laurent: tronçon Varennes-Montmagny. Rapport scientifique No 48,* Institut National de la Recherche Scientifique (INRS-Eau), Sainte-Foy, Québec.

Cossa, D. 1990. Chemicals contaminants in the St. Lawrence Estuary and Saguenay Fjord. *Oceanography of a Large -Scale Estuarine System. The St. Lawrence. Coastal and Estuarine Studies,* 39: 239-268. M.I. El-Sabh, N. Silverberg (EDS). Springer-Verlag New York Inc.

Couillard, D. 1987. Qualité des sédiments en suspension et de fond du système Saint-Laurent (Canada). *Hydrological Sciences - Journal des Sciences Hydrologiques* 32 (4,12): 445-467.

D'Anglejan, B.F. 1990. Recent sediments and sediment transport processes in the St. Lawrence Estuary. *Oceanography of a large-scale estuarine system: The St. Lawrence, Coastal and Estuarine Studies* 39: 109-129, Springer-Verlag, New York.

D'Anglejan, B.F. and M. Brisebois. 1978. Recent sediments in the St. Lawrence Middle Estuary. *J. Sedim. Petrol.* 48(3): 951-964.

Dionne, J.C. and D. Brodeur. 1988. Érosion des plates-formes rocheuses littorales par affouillement glaciel. *Z. Geomorph. N.F.* 32(1): 101-115.

Dolske, D.A. and H. Silvering. 1979. Trace element loading of southern Lake Michigan by dry deposition of atmospheric aerosol. *Water, Air and Soil Pollution.* pp. 485-502.

Drapeau, G. 1990. Nearshore sediment dynamics in the St. Lawrence Estuary. *Oceanography of a large-scale estuarine system: The St. Lawrence, Coastal and Estuarine Studies* 39: 130-154, Springer-Verlag, New York.

Dunbar, M.J., D.C. MacLellan, A. Filion and D. Moore. 1980. *The biogeographic structure of the gulf of St. Lawrence.* Marine Science Center Manuscript 32, McGill University, Montréal, 142 p.

El-Sabh, M.I. 1975. Transport and currents in the Gulf of St. Lawrence. *Bed. Inst. Oceanogr. Rep.* Ser./BI-R-75-9, 180 p.

El-Sabh, M.I. 1976. Surface Circulation Pattern in the Gulf of St. Lawrence. *J. Fish. Res. Board Can.* 33: 124-138.

Environment Canada. 1990. *Sommaire chronologique de l'écoulement au Québec jusqu'à 1989.* Inland Waters Directorate, Québec Region.

Environment Canada. 1991a. *Atlas environnemental du Saint-Laurent - Milieu naturel. Un fleuve, des estuaires, un golfe, les grandes divisions hydrographiques du Saint-Laurent.* St. Lawrence Centre, Knowledge of the State of the Environment Division, Conservation and Protection, Montréal.

Environment Canada. 1991b. *Atlas environnemental du Saint-Laurent - Milieu naturel. Les milieux humides : des habitats au contact de la terre et de l'eau.* Knowledge of the State of the Environment Division, Conservation and Protection, Montréal.

Environnement Illimité Inc. 1990. *Caractérisation du port de Montréal. Rapport final.* Prepared for the Environmental Portection Directorate, Conservation and Protection, Environment Canada.

Environnement Illimité Inc. and Lavalin Environnement. 1991. *Secteurs aquatiques contaminés du port de Montréal. Plans d'intervention - Phase 1 : Rapport final.* Vol. 1-3. Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Fisheries and Oceans. 1992. *Tables des marées et courants du Canada.* Vol. 3: St. Lawrence and Saguenay Rivers, Ottawa, 33 p.

Frenette, M. and J.L. Verrette. 1976. Environnement physique et dynamique du fleuve Saint-Laurent. *L'Ingénieur,* 312: 13-28.

G.D.G. Environnement Ltée. 1990. *Caractérisation de la qualité des sédiments du port de Trois-Rivières. Rapport final.* Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Gobeil, C. and D. Cossa. 1984. Profils des teneurs en mercure dans les sédiments et les eaux interstitielles du fjord du Saguenay (Québec) : données acquises au cours de la période 1978-1983. *Rapp. techn. Can. Hydrogr. Sci. Océan.* No 53.

Gobeil, C. and N. Silverberg. 1989. Early diagenesis of lead in Laurentian Trough sediments. *Geochim. Cosmochin. Acta.* 53: 1889-1895.

Gobeil, C. 1991. Inventaire de la contamination des sédiments du chenal Laurentien: Données sur les métaux et les éléments nutritifs." *Fisheries and Oceans Canada. Rapp. stat. can. sci. halieut. aquat.* 854: 63 p.

Godin, G. 1979. La marée dans le fleuve et l'estuaire du Saint-Laurent. *Nat. Can.* 106 (1): 105-121.

Hardy, B., J. Bureau, L. Champoux and H. Sloterdijk. 1991a. *Caractérisation des sédiments de fond du Petit bassin de La Prairie, fleuve Saint-Laurent.* St. Lawrence Centre, Environment Canada.

Hardy, B., L. Champoux, H. Sloterdijk and J. Bureau. 1991b. *Caractérisation des sédiments de fond du lac Saint-Pierre, fleuve Saint-Laurent.* St. Lawrence Centre, Environment Canada.

Hydrotech Inc. 1982. *Projet Archipel. Étude des aspects hydro-sédimentologiques. Rapport d'étape.* Prepared for Hydro-Québec, Division études spéciales et recherche.

Hydrotech Inc. 1989. *Aspects quantitatifs, dynamiques et qualitatifs des sédiments du Saint-Laurent.* Prepared for Environment Canada, Québec Region.

Hydrotech Inc. 1990. *Fleuve Saint-Laurent. Priorisation et caractérisation des fonds contaminés. Rapport final.* Prepared for Environment Canada.

Jaagumaji, R. 1992. *Development of the Ontario Provincial Sediment Quality Guidelines for Arsenic, Cadmium, Chromium, Copper, Iron, Lead, Manganese, Mercury, Nickel, and Zinc.* Water Resources Branch, Ontario Ministry of the Environment.

Jarry V., P. Ross, L. Champoux, H. Sloterdijk, A. Mudroch, Y. Couillard and F. Lavoie. 1985. Répartition spatiale des contaminants dans les sédiments du lac Saint-Louis (fleuve Saint-Laurent). *Water Poll. Res. J. Canada* 20(2): 75-99.

Kauss, K.L.E., Y.S. Hamdy and B.S. Hamma. 1988. *St. Lawrence River Environmental Inverstigations. Vol 1 - Background: Assessment of Water, Sediment and Biota in the Cornwall, Ontario and Massena, New York Section of the St. Lawrence River, 1979-1982.* Water Resources Branch, Environment Ontario, Toronto, Ontario, 157 p.

Keighan, E. 1977. *Caractérisation du niveau d'enrichissement et de la toxicité des eaux du bassin du fleuve Saint-Laurent.* Technical report 6 for the Saint Lawrence River Study Committee, by Fisheries and Oceans and Environment Canada.

Koutitonsky, V.G. and G.L. Bugden. 1991. The physical oceanography of the Gulf of St. Lawrence: a review with emphasis on the synoptic variability of the motion. *The Gulf of St. Lawrence: Small Ocean or Big Estuary? Can. Spec. Publ. Fish. Aquat. Sci. 57-90.* Fisheries and Oceans, Ottawa.

Lavalin. 1984. *Les substances toxiques dans le moyen estuaire du Saint-Laurent.* Inland Waters Directorate, Environment Canada, Québec Region.

Lavalin Environnement Inc. 1989. *Sites aquatiques contaminés du Saint-Laurent. Inventaire et priorisation. Rapport final.* Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Loring, D.H. and D.J.G. Nota. 1973. Morphology and sediments in the Gulf of St. Lawrence. *Fish. Res. Board Can. Bull. 182,* 147 p.

Loring, D.H. 1975. Mercury in the sediments of the Gulf of St. Lawrence. *Can. J. Earth Sc.,* 12: 1219-1237.

Loring, D.H. 1978a. Geochemistry of zinc, copper and lead in the sediments of the estuary and open gulf of St. Lawrence. *Can. J. Earth Sci.,* 15: 757-772.

Loring, D.H. 1978b. Industrial and natural inputs, levels, behaviour, and dynamics of biologically toxic heavy metals in the Saguenay Fjord, Gulf of St. Lawrence, Canada. *Proceedings of the 111th Intern. Symp. Environ. Biogeochem.* 3: 1025-1040. Krumbein, W.E. (ed.) Ann Arbor Sci. Publish., Ann Arbor, USA.

Loring, D.H. 1979. Geochemistry of cobalt, nickel, chromium and vanadium in the sediments of the estuary and open Gulf of St. Lawrence. *Can. J. Earth Sci.,* 16: 1196-1209.

Loring, D.H. and J.M. Bewers. 1978. Geochemical mass balances for mercury in a Canadian fjord. *Chem. Geol.,* 22: 309-330.

Loring, D.H., R.T.T. Rantala and J.N. Smith. 1983. Response time of Saguenay Fjord sediments to metal contamination. *Environmental Biogeochemistry Ecol. Bull.* 35: 59-72. R. Hallberg, ed., Stockholm.

Lorrain, S. and V. Jarry. 1992a. *Répartition spatiale de la contamination des sédiments au lac Saint-François en 1989; métaux traces, contaminants organiques.* St. Lawrence Centre, Environment Canada.

Lorrain, S., V. Jarry and K. Guertin. 1992b. *Répartition spatiale et évolution temporelle des biphényles polychlorés et du mercure dans les sédiments du lac Saint-François; 1979-1989.* St. Lawrence Centre, Environment Canada.

Lucotte, M. and B.F. d'Anglejan. 1986. Seasonal control of the St. Lawrence maximum turbidity zone by tidal-flat sedimentation. *Estuaries* 9 (2): 84-94.

Luoma, S.N. 1983. Bioavailability of trace metals to aquatic organisms: a review. *Sci. Tot. Environ.,* 28: 1-22.

Malo, D. 1978. *Les sources de polluants. Rapport d'étude sur le tronçon en aval de Montmagny.* Report for the St. Lawrence River Study Committee, 4: 821-882.

Malo, D, and D. Gouin. 1977. *Caractérisation des apports.* Technical Report 14 for the St. Lawrence River Study Committee, by the Envrionment Protection Service, Government of Québec.

Moore, J.N., W.H. Ficklin and C. Johns. 1988. Partitioning of arsenic and metals in reducing sulfidic sediments." *Environ. Sci. Technol.* 22: 432-437.

MUC. 1988. *Sédiments, granulométrie, métaux et contaminants organiques.* Montréal Urban Community, Environment Services, Ecological Monitoring Program.

Ouellet, Y. and J. Llamas. 1979. Complément et analyse des hauteurs de vagues dans le golfe du Saint-Laurent. *Nat. Can.* 106(1): 123-139.

Pageau, G. 1971. *La valeur des indices physicochimiques dans la distinction des trois masses d'eau du lac Saint-Louis.* Québec Department of Tourism, Hunting and Fishing, Wildlife Service. Report 6: 1-14.

Pelletier, E. and G. Canuel. 1988. Trace metals in surface sediments of the Saguenay Fjord, Canada. *Mar. Pollut. Bull.,* 19: 336-338.

Préfontaine, G. 1942. Étude biologique des eaux de la plaine de Montréal et description générale des eaux de la plaine de Montréal. *Station Biol. Montréal, Inst. Biol. Univ. Montréal, fascicule 1:* 33-67.

Procéan Inc. 1990. *Caractérisation de la qualité des sédiments du port de Québec. Final Report.* Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Procéan Inc. 1991a. *Plan d'intervention des secteurs aquatiques contaminés du port de Québec. Secteur PIQ2, Phase 1. Bassin Louise intérieur et extérieur.* Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Procéan Inc. 1991b. *Plan d'intervention des secteurs aquatiques contaminés du port de Québec. Secteur PIQ1, Phase 1. Estuaire de la rivière Saint-Charles.* Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Procéan Inc. 1992a. *Plan d'intervention des secteurs aquatiques contaminés du port de Québec. Secteur PIQ2, Phase 2. Bassin Louise : Caractérisation détaillée.* Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Procéan Inc. 1992b. *Plan d'intervention des secteurs aquatiques contaminés du port de Québec. Secteur PIQ1, Phase 2. Estuaire de la rivière Saint-Charles : Caractérisation détaillée.* Prepared for the Environmental Protection Directorate, Conservation and Protection, Environment Canada.

Roche Associés. 1983. *Forages hauturiers d'exploration dans le golfe du Saint-Laurent. Étude des répercussions environnementales.* Report prepared for SOQUIP.

Rudd, J.W.M., M.A. Turner, A. Furutani, A. Swick and B.E. Townsend. 1983. The English-Wabigoon River system: I. A synthesis of recent research with a view towards mercury amelioration. *Can. J. Fish. Aquat. Sci.* 40: 2206-2217.

Schafer, C.T., J.N. Smith and R. Côté. 1990. The Saguenay Fjord: a Major Tributary to the St. Lawrence Estuary. *Oceanography of a large-scale estuarine system: The St. Lawrence, Coastal and Estuarine Studies* 39: 378-429. Springer-Verlag, New York.

Sérodes, J.B. 1978. *Qualité des sédiments de fond du fleuve Saint-Laurent entre Cornwall et Montmagny. Rapport technique No 15.* Prepared for the St. Lawrence River Study Committee.

Sérodes J.B. and L. Talbot. 1978. *Projet de restauration du sud du lac Saint-Louis contaminé par le mercure.* BEST and Inland Waters Directorate, Fisheries and Oceans and Environment Canada.

Shepard, F.P. 1954. Nomenclature based on sand-silt ratios. *Jour. Sed. Petrology 24:* 151-158.

Sloterdijk, H. 1985. *Substances toxiques dans les sédiments du lac Saint-François.* Inland Waters Directorate, Environment Canada, Québec region, 75 p.

SLRT (St. Lawrence Rap Team). 1991. *The St. Lawrence Area of Concern Remedial Action Plan for the Cornwall-Lake St. Francis Area. Stage 1 Report: Environmental Conditions and Problem Definitions.* Environment Canada and Ontario Ministry of the Environment.

St. Lawrence Centre and the Québec Department of the Environment. 1992. *Critères intérimaires pour l'évaluation de la qualité des sédiments du Saint-Laurent.* 28 p.

Sturton, A.H.G. 1970. *Mercury in Beauharnois Plant Water Effluent.* Standard Chemicals Ltd., 4 p.

Sydor, M. 1978. *Étude d'un modèle bidimensionnel pour le fleuve Saint-Laurent. Rapport technique No 16.* Prepared for the St. Lawrence River Study Committee.

Trites, R.W. 1972. The Gulf of St. Lawrence from a pollution point of view. *Marine Pollution and Sea Life,* FAO, Fishing New Books, London. pp. 59-72.

Troude, J.P. and J.B. Sérodes. 1983. *Étude des mécanismes sédimentologiques des zones intertidales de l'estuaire moyen du Saint-Laurent. Cas de la batture de Pointe-aux-Prêtres (Batture de Cap-Tourmente).* Inland Waters Directorate, Environment Canada, Québec Region, 69 p.

Troude, J.P. and J.B. Sérodes. 1988. Le rôle des glaces dans le régime morphosédimentologique d'un estran de l'estuaire moyen du Saint-Laurent. *Can. J. Civ. Eng.* 15: 348-354.