

Potential Ecological Effects of the Proposed GRAND Canal Diversion Project on Hudson and James Bays

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ABSTRACT. The GRAND Canal scheme, which by the construction of a dike across James Bay would divert 61% of Hudson Bay's freshwater budget south, has ecological implications for the North. The formation of ice in Hudson Bay could increase as its pycnocline develops earlier in the spring and deepens in the summer and ice breakup is delayed because of the removal of the warm James Bay outflow in the spring. A reduction in primary productivity could result because of changes in the pycnocline's development, the removal of nutrients normally associated with spring's melting ice and a decrease in stable stratification periods as the dike removes the dampening action of James Bay on tidal and wind-generated disturbances.

Changes in nutrient content and freshwater circulation out of Hudson Bay could potentially affect productivity downstream on the Labrador Shelf, and changes in productivity and ice pack within Hudson Bay would detrimentally affect fishes and marine mammals. Changes to coastal staging areas in both bays would most likely destroy a major portion of the North American migratory bird population.

A resurgence of interest in the GRAND Canal scheme necessitates further research to provide data for the many unanswered questions concerning the potential ecological impacts of the diversion.

Key words: GRAND Canal, diversion, Hudson Bay, James Bay, pycnocline, phytoplankton, productivity, ecological impact, climate modification

RÉSUMÉ. Le projet du GRAND Canal qui doit détourner 61% du volume d'eau douce de la baie d'Hudson vers le Sud grâce à la construction d'une digue traversant la baie James, a des implications écologiques pour le Nord. La formation de la glace dans la baie d'Hudson pourrait augmenter si sa pycnocline se formait plus tôt au printemps et s'enfonçait au cours de l'été, et si la rupture des glaces dans la baie d'Hudson avait lieu plus tard à cause de la suppression de l'écoulement des eaux tempérées de la baie James au printemps. Il pourrait s'ensuivre une diminution de la productivité primaire à cause de changements dans la formation de la pycnocline, de l'élimination des éléments nutritifs associés d'ordinaire à la fonte des glaces au printemps, et aussi à cause d'une diminution des périodes stables de stratification, la digue supprimant l'effet d'atténuation de la baie James sur les perturbations créées par les marées et par les vents.

Des changements dans le contenu en éléments nutritifs et dans la circulation de l'eau douce qui sort de la baie d'Hudson, pourraient éventuellement affecter la productivité en aval sur le plateau continental du Labrador. Or, des changements dans la productivité et dans la banquise à l'intérieur de la baie d'Hudson auraient des effets néfastes sur les poissons et les mammifères marins. Des changements dans les zones côtières des deux baies qui servent d'étape, amèneraient presque certainement la destruction d'une très grande partie de la population d'oiseaux migrateurs d'Amérique du Nord.

Un regain d'intérêt pour le projet du GRAND Canal doit s'accompagner de plus amples recherches pour fournir des données permettant de répondre aux nombreuses questions qui subsistent quant au risque de retombées écologiques associées à ce détournement d'eau.

Mots clés: GRAND Canal, détournement, baie d'Hudson, baie James, pycnocline, phytoplancton, productivité, retombée écologique, changement climatique

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INTRODUCTION

There has recently been a resurgence of interest in the Great Replenishment and Northern Development (GRAND) Canal scheme (Bourassa, 1985). This scheme would involve the construction of a dike across James Bay (Fig. 1), creating a large freshwater lake, and the transferring of this freshwater by way of canals and existing water courses to the Great Lakes and various other areas of the United States and Canada. Although the parameters of the project have not yet been clearly defined, one likely scenario would involve the total withdrawal of all freshwater flowing from James Bay into Hudson Bay (Bourassa, 1985), i.e., 61% of the freshwater budget of Hudson Bay or 317 km³·yr⁻¹ (Prinsenberg, 1980).

Despite the fact that the Hudson Bay drainage area includes more than three million km², has an annual average discharge rate more than twice that of either the Mackenzie or St. Lawrence rivers and contains the largest body of water in the world that largely freezes over each winter and becomes ice free during the summer, Hudson Bay has only been marginally studied (Prinsenberg, 1980). In the 1970s, hydroelectric developments on rivers that flow into James Bay prompted an increase in studies of James and Hudson bays, with research predominantly focused on James Bay. In view of the resurgence of interest in the GRAND Canal scheme, an assessment of the potential ecological impacts of this scheme on both of these

northern bodies of water warrants attention. It is predominantly from the scant, recently collected information that predictions of the effects of terminating the flow of freshwater from James Bay into Hudson Bay must be made.

In order to speculate on these impacts, the oceanographic parameters of Hudson and James bays must first be understood. Consequently, this paper first briefly summarizes some of these parameters, with an emphasis on those of Hudson Bay. Second, the paper examines some similar large-scale diversions elsewhere, which should help to illustrate the effects or potential effects of large-scale water diversions. Thirdly, possible impacts on the oceanographic and ecological parameters of Hudson Bay and James Bay resulting from the construction of a dike that would terminate the flow of freshwater between these bodies of water are examined.

OCEANOGRAPHIC DESCRIPTION

Hudson Bay is part of a large inland sea connected to the Atlantic Ocean by Hudson Strait and the Labrador Sea and to the Arctic Ocean by Fury and Hecla Strait. Hudson Bay has an average depth of 125 m and an approximate rectangular shape of 925 × 700 km. James Bay is much shallower, seldom deeper than 50 m, and with an average depth of 28 m; it is 150 km wide and 400 km long.

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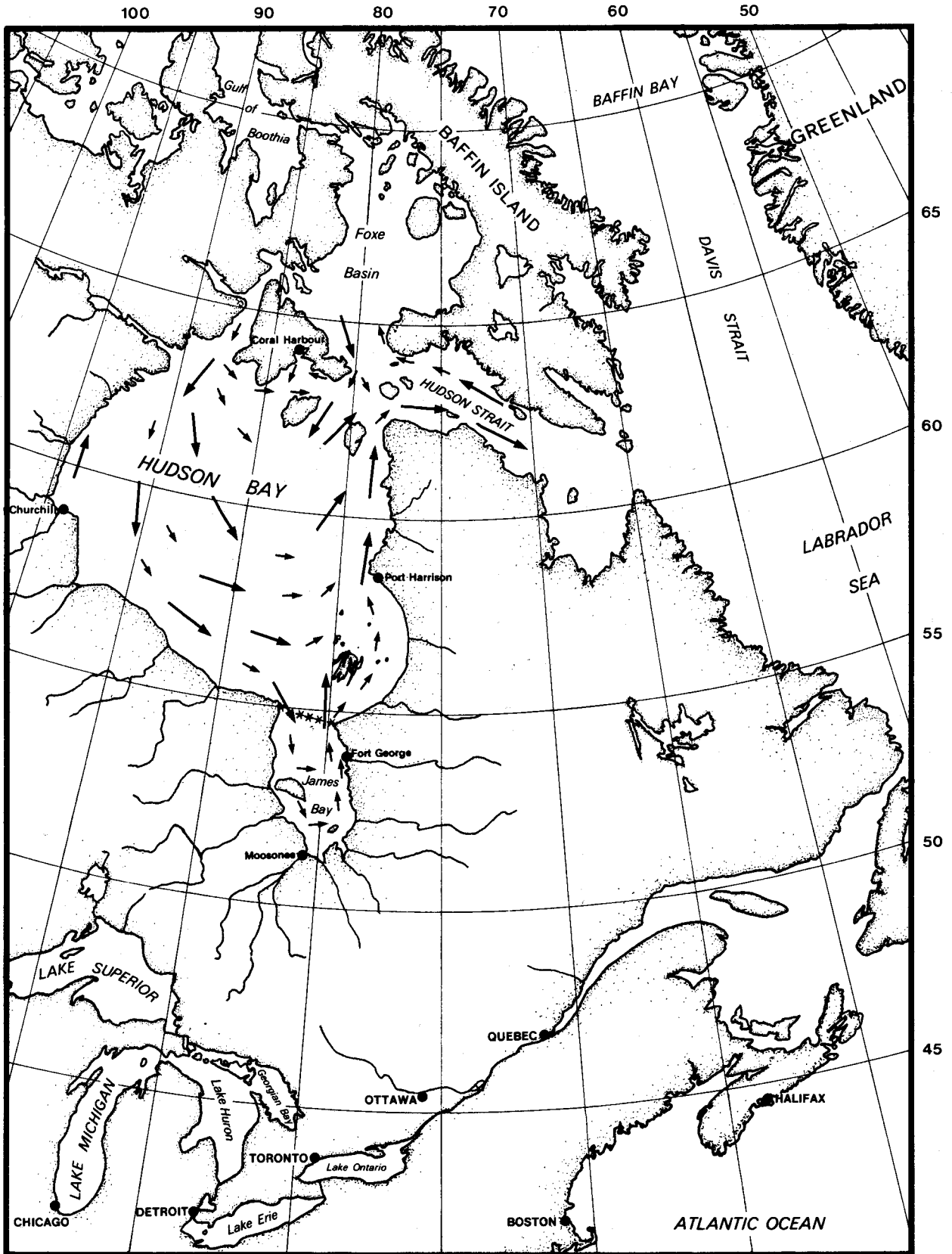


FIG. 1. Location map of Hudson Bay and James Bay illustrating summer surface circulation patterns and possible location of the dike (adapted from Prinsenberg, 1986a).

Circulation

Hudson Bay is believed to behave as a huge estuarine basin with fresher, less dense water flowing out at the surface and denser saltwater moving in at depth (Pett and Roff, 1982). Because of sills and varying depths at the entrance to Hudson Bay, deepwater exchange appears to occur predominantly by way of one central channel, with some winter influx by way of a shallower channel to the north and west of Southampton Island. Saltwater inflow into Hudson Bay through these two channels has been estimated at $0.5 \times 10^6 \text{ m}^3 \cdot \text{s}^{-1}$ and 0.05 to $0.1 \times 10^6 \text{ m}^3 \cdot \text{s}^{-1}$ respectively (Dunbar, 1982). The water that enters the bay is heavier, sinking below the surface layer, and does not show up as surface flow (Prinsenber, 1986a).

Figure 1 shows the summer surface circulation pattern of Hudson and James bays. In Hudson Bay, the southeasterly surface circulation is predominantly wind-driven in the summer and autumn, resulting in a cyclonic pattern with an average speed of $5 \text{ cm} \cdot \text{s}^{-1}$. The circulation is also partially driven by density currents as a result of dilution because of freshwater runoff. Surface outflow is predominantly through Hudson Strait to the north ($9 \text{ cm} \cdot \text{s}^{-1}$) and is seasonal in response to the freshwater input cycle. The absence of a northwestward return flow results in an upwelling region along the northwestern shore where deeper water partially replaces the offshore component of the surface flow to the southeast.

Circulation in James Bay comprises a cyclonic gyre, driven partly by wind stress and by runoff dilution. This also results in an estuarine circulation where cold saline water enters James

Bay from Hudson Bay beneath the fresher surface layer (Prinsenber, 1986a) and exits in a strong northerly surface outflow ($15 \text{ cm} \cdot \text{s}^{-1}$ in the summer) along the eastern shore into Hudson Bay.

Salinity, Temperature and Seasonal Distributions

Data in all seasons are lacking for Hudson Bay but are somewhat more complete for James Bay. Generally, the less saline water is found along the south and east shores of Hudson Bay (Prinsenber, 1982), and unlike the case in Hudson Strait, a temperature increase associated with a more saline deep layer of Atlantic water is not found. Cross-sectional surveys have indicated that below the surface layer the water continually becomes colder and more saline with depth. At 100 m, the water has an average salinity greater than 33‰ and is colder than -1.4°C . Offshore salinities in areas adjacent to major rivers in James Bay can be as low as 10‰, with the lowest salinities occurring in the summer because of increased runoff and melting of the ice cover (Prinsenber, 1986b).

A simple description of circulation can be envisioned as cold subsurface water with a salinity of 33.4‰ or greater entering Hudson Bay from Hudson Strait, while the surface water, moving north along the eastern shore, is a water mass warmed by solar radiation and diluted by runoff. The outflow temperature and salinity are somewhat modified by vertical mixing with the subsurface waters as they circulate through Hudson Bay.

Although insufficient data are available to accurately model seasonal variations of salinity and temperature, some general

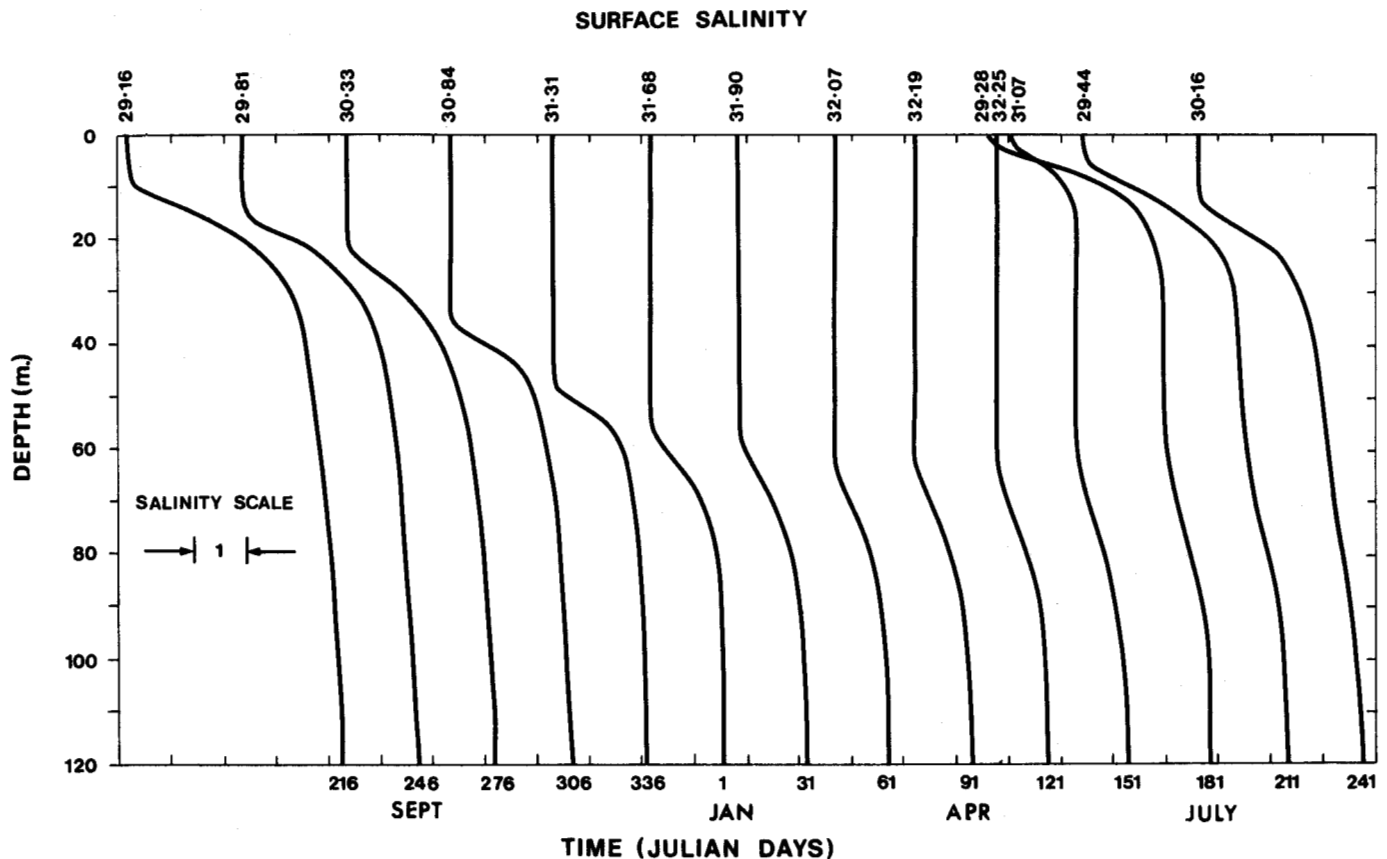


FIG. 2. Annual cycle of salinity profiles for Hudson Bay as predicted by a mixed-layer model (from Prinsenber, 1983). Each profile is stepped to the right by 1.5 salinity units and its surface salinity is noted at the top of each profile. The time of occurrence at 30-day intervals is denoted in Julian days and months at the bottom of the profiles (Prinsenber, 1986b).

observations can be made. The pycnocline (boundary separating a relatively freshwater layer over a saltwater layer with little mixing), established in conjunction with surface runoff in the spring, progresses to greater depths as the season advances, reaching a maximum depth of 93.5 m at the end of the following winter (Fig. 2). Below the pycnocline (average depth of 25 m) water properties remain relatively constant, but above the pycnocline vertical mixing redistributes solar input to produce a relatively homogeneous water temperature that contains 74% of the total heat input to the bay (Prinsenber, 1984).

Freshwater Input

Because ice is relatively fresh (5‰), ice cover and runoff have been calculated to be major and equal components of the freshwater flux of Hudson Bay (Prinsenber, 1984). Their individual contributions are described below.

In Hudson Bay the ice cover starts to form in northern areas by late October and continues to grow until a maximum cover is reached at the end of April. An average ice thickness of 1.75 m is found in northern Hudson Bay but reduces to an average of only 1 m in southern James Bay (Markham, 1981). Polynyas (open water leads in the ice) are found predominantly along the northwest and east coasts of Hudson Bay, both coasts of James Bay and west of the Belcher Islands joining the two mainland masses (EMR, 1974).

Aerial surveillance has now documented the extent of ice cover (Markham, 1981) and its seasonality. Decay of the ice cover commences in late May, rapidly releasing this source of stored freshwater throughout June and July. Breakup in Hudson Bay, aided by predominant northwest winds, occurs from north to south and east to west. Although this freshwater addition from the melting ice is approximately equal or larger in volume to that of runoff and will contribute to the estuarine cyclonic circulation of Hudson Bay, it does not affect the overall salinity of the bay but only redistributes the salt and freshwater vertically. In this regard it contributes as much to the water column stability as does the surface runoff.

In contrast to Hudson Bay, the ice of James Bay breaks up from south to north, with the bay usually ice free by the end of July. The timing and pattern for James Bay's breakup is strongly dependent upon the large quantity of relatively warm freshwater of the spring runoff (Prinsenber, 1980). Consequently, this relatively warm surface outflow from James Bay initiates the early breakup of the ice in southeast Hudson Bay.

Runoff is a function of both spring melt and precipitation (Prinsenber, 1986b). In Hudson Bay the mean runoff per unit drainage area increases from north to south, with a maximum value in south James Bay. On a seasonal basis, a maximum runoff for both bays occurs with the spring freshet of May and June (Fig. 3). In James Bay, however, a secondary peak of runoff occurs during the pronounced rainy season (October) of the southern region. Here the precipitation rates are nearly double those of Hudson Bay and balance the loss of water resulting from evaporation. In contrast, Hudson Bay acts more as an oceanic region and loses more in evaporation than it gains from precipitation.

In summary, freshwater input cycles calculated from runoff, precipitation and evaporation can be divided into a winter and summer season. During the summer, the entire surface area of both bays gains a 10 cm layer of freshwater per month, which decreases to a 0.5 cm layer during the winter. Over the year, the

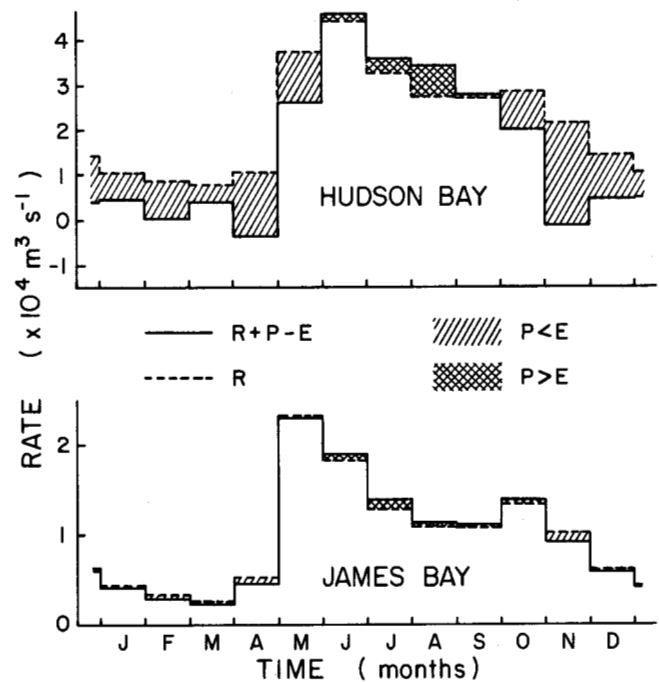


FIG. 3. Rates of monthly freshwater input for Hudson Bay and James Bay including contributions from runoff (R), precipitation (P) and evaporation (E) (Prinsenber, 1986b).

region receives a 64 cm layer of freshwater ($523 \text{ km}^3 \cdot \text{yr}^{-1}$), equal to 0.5% of its total volume. Of this, James Bay accounts for 61% ($317 \text{ km}^3 \cdot \text{yr}^{-1}$), which indicates its importance to the freshwater budget of Hudson Bay (Prinsenber, 1980).

The heat budget shows that the ice cover and the water column are the main benefactors of the incoming surface heat flux and that heat advection in and out of Hudson Bay by currents are negligible (Prinsenber, 1986b). In James Bay, however, strong horizontal advection out of the entrance is found and contributes to the early melting of ice in southeast Hudson Bay in the spring. The results of the freshwater and heat budget show that the annual ice cover, runoff and heat content of the surface water are closely related (Prinsenber, 1986b). Changes in one will affect the others.

EFFECTS OF FRESHWATER FLOW AND DIVERSIONS

A primary reason for estuaries, embayments and continental shelves being fertile, productive regions is the supply of freshwater from land runoff, which deposits nutrients directly and, on entering the ocean, induces mixing and the entrainment of nutrient-rich deepwater to the surface. Particularly in higher latitudes, nearshore biological processes and adjacent ocean activities are attuned to this massive seasonal influx. A freshwater flow encountering saltwater results in the formation of a density current or haline circulation system such as that which helps to drive the estuarine circulation of Hudson Bay. The effect of a density current is to impose a two-layer flow system which, in an estuary, causes the surface layer of freshwater to flow outward and the deeper (often nutrient-rich) bottom saltwater to flow shoreward. The magnitude of the current will of course be proportional to the pressure difference, and in an unregulated system pulses of current occur as a result of

seasonal runoff. It is possible that a reduction of a density current could result in a reduction in productivity.

An example is that of the St. Lawrence River and the Scotian Shelf and Grand Banks (Fig. 4). The density current from the St. Lawrence freshwater flow results in deepwater from the continental shelf penetrating more than 1500 km upstream without any significant contact with the freshwater. Over large distances such as to the Grand Banks, there can be delays from several months to a year before a freshwater peak arrives. Regulation of the St. Lawrence River via the Manicougan-Outardes-Bersimis hydroelectric power complex commenced in the 1960s and retained up to $8000 \text{ m}^3 \cdot \text{s}^{-1}$ by the spring of 1970 (one-quarter to one-third of the peak discharge of the St. Lawrence). This resulted in an approximate 1.3‰ increase in summer salinity of the surface layer at Cabot Strait and a drastic reduction in cyclic (seasonal) variation of salinities when compared to the unregulated condition (Neu, 1975, 1982a). Neu contends that this storage scheme had and continues to have an impact on the biological resources of the Atlantic coastal region. He estimates a 20-30% reduction of nutrients entering the system during the biologically active period and illustrates the relationship between varying flow rates and fish stocks — i.e., the larger the runoff, the greater the yield (Neu, 1975, 1982a,b). Data to prove the effect are admittedly masked by other possibilities such as changes in fishing levels, but the discussion is worthy of consideration.

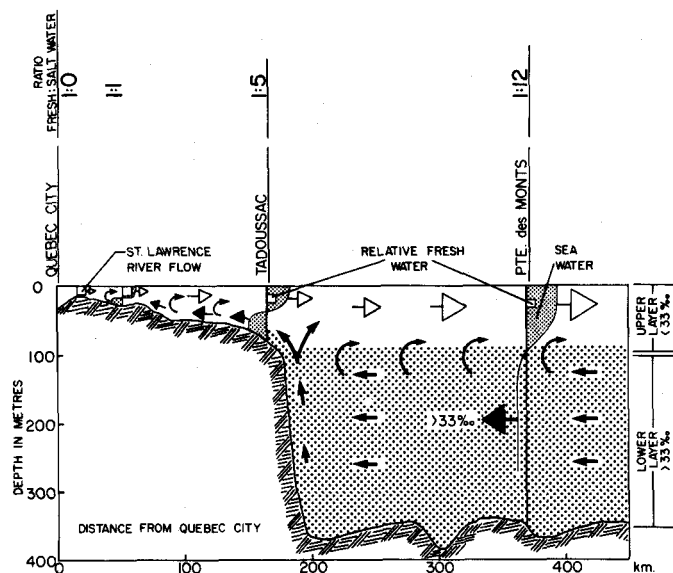


FIG. 4. Schematic representation of haline circulation (density currents) in the St. Lawrence River system (Neu, 1975).

Considerable concern has been expressed about possible climate modification as a result of large-scale water diversions of north-flowing rivers. In particular, plans developed in 1976 by the U.S.S.R. to divert water from rivers flowing into the Arctic led to some research into the impact of a reduction in the natural discharge on arctic sea ice. Water transfer proposals, scheduled to commence in 1986 (Micklin, 1985), although now delayed or possibly cancelled (New Scientist, 1986), involved the withdrawal of $60 \text{ km}^3 \cdot \text{yr}^{-1}$ from the European North of the U.S.S.R. and $60 \text{ km}^3 \cdot \text{yr}^{-1}$ from the Siberian region, with a possible additional withdrawal of up to $100 \text{ km}^3 \cdot \text{yr}^{-1}$ during the

21st century. In comparison, the total withdrawal of James Bay's freshwater would amount to $317 \text{ km}^3 \cdot \text{yr}^{-1}$. Since sea-ice concentration data for the Arctic and its marginal seas correlate significantly with variations in discharges of Siberian rivers, several mechanisms affecting localized and large-scale sea-ice cover are worthy of investigation. The first three of five mechanisms that might be considered with respect to the U.S.S.R. diversions involve local or regional impacts (Holt *et al.*, 1984):

- (1) A reduction in river flow could result in delayed removal of fast ice (ice attached to the shore) or a reduction in removal of broken fast ice.
- (2) Reduced heat influx, i.e., warm freshwater, could result in early ice formation in the autumn.
- (3) A reduction of freshwater could result in a higher salinity, which could lead to delayed or reduced ice formation in the autumn.

Hypotheses concerning mechanisms that have large-scale effects are more complex. Two are outlined below:

- (4) Density gradients result in an inflow of warm Atlantic water, which, because of its high salinity (density), sinks below the colder, less dense arctic water. The halocline in this arctic region functions as a marked pycnocline and forms a barrier that suppresses heat flow from the deep Atlantic water to the surface. It has been suggested that a reduction in river flow could lead to a subsequent thinning of the pycnocline, allowing the deep, warm Atlantic layer to reach the surface. This could result in large ice-free areas and a general warming trend.

- (5) Conversely, less freshwater outflow could produce a weaker density current, reducing the warming effect of the Atlantic. This might result in colder overall temperatures and an increase in ice cover.

Modelling of the river flows and ice pack conditions suggests that a reduction of river discharges could result in local increases of ice in some areas and decreases of ice in others. On a large scale, modelling of mechanism (5) (above) suggests a reduced density current and an increase of ice cover are possible; mechanism (4) (above) could not be similarly modelled because of a lack of empirical data.

A numerical model examining these diversions in the U.S.S.R. suggests some erosion of the stable stratification in the Kara and Barents seas but not to the point of convective instability. As well, little change in the extent of sea ice, except for possible local minor thickening, was predicted (Semtner, 1984).

Opinion is divided over whether the gross effects would be an overall warming or cooling, two diametrically opposed results; however, the weight of opinion and evidence points to a cooler Arctic (Semtner, 1984; Micklin, 1985). If, however, a decreased ice pack was a result, it has been suggested that this, coupled with the greenhouse effect, could reduce rainfall in the very areas expecting to benefit from the diversions (Gribbin and Kelly, 1979).

POTENTIAL EFFECTS OF CHANGES TO HUDSON BAY

Ice Pack and Climate

Although Hudson Bay is governed by somewhat different oceanographic parameters, there are enough similarities to the U.S.S.R. scenarios that the three mechanisms governing local effects on ice pack can be considered to be possible results of

diverting the freshwater flow of James Bay south. In fact, the freshwater withdrawal of the GRAND Canal could potentially be 44% greater than the diversion volumes used in the U.S.S.R. models. The present local and regional effect of the Hudson and James bays' ice pack on the weather patterns and flora in central Canada is witnessed by the southward dipping of the treeline as the bays are approached. Considering the dependence of treeline on the delicate balance of climatic parameters, any modification to ice pack duration could affect the local or regional climate. Predictions of localized climate effects were even made for much smaller-scale developments such as the La Grande on James Bay (Environment Canada, 1975). The large-scale effects of mechanism (4) (i.e., warming trend) seem unlikely for Hudson Bay, as there is not a warm subsurface layer to be released to the surface. An effect on the pycnocline and the water column stability of Hudson Bay is, however, quite possible.

A one-dimensional oceanic mixed-layer model simulating the annual surface layer properties of Hudson Bay indicates their sensitivity to runoff modification (Prinsenber, 1983). The model is simplistic, partly due to the lack of available data and the number of variables examined, but it does simulate some effects of hydroelectric developments. It does not, however, simulate a condition as extreme as withdrawal of all the freshwater contributed by James Bay (only one of the many scenarios possible from the so-far vaguely described GRAND Canal scheme). Results of the model indicate that, due to runoff modification brought about by hydroelectric developments, the shallow surface pycnocline of Hudson Bay would be formed earlier in the spring, decreasing the surface layer temperature and salinity and thus stimulating an increase in ice formation as vertical mixing is reduced. In the summer, the surface layer salinity would be higher and the temperature would be lower, which would decrease the water column stability. As a result, the pycnocline would deepen, which would increase the deviations from normal conditions (Prinsenber, 1983).

As discussed earlier, there is a strong net flow of warm water out of James Bay each spring, which contributes to the early melting of southeast Hudson Bay (Prinsenber, 1984, 1986b). It is quite likely that damming James Bay and removing its spring outflow into Hudson Bay would result in a delay in ice breakup in southeast Hudson Bay. In conjunction with an increase in ice formation as vertical mixing is reduced, the possibility of ice pack and climate modification seems more likely. Interestingly, a more complex atmospheric model suggests that the sea surface temperature may be buffered against man-made changes. This model indicates that "a one-degree depression of sea surface temperature in the summer is slowly offset by increased heating and no noticeable change in temperature remains at the end of the fall" (Prinsenber and Danard, 1985).

Primary Productivity

Based on the model (Prinsenber, 1983) simulating a 25% ice layer reduction, which is equivalent to a 50% reduction of James Bay freshwater flow, a total diversion of James Bay freshwater might result in only a 1% increase in salinity in the summer surface layer of Hudson Bay (Prinsenber, 1983; Prinsenber, pers. comm. 1985). If this is the case, salinity modification of Hudson Bay may have less biological impact than one might imagine. However, further ramifications of the reduced stability and deeper pycnocline could involve a reduc-

tion in primary productivity. Offshore phytoplankton are found in a 20 m layer below the pycnocline where their chlorophyll concentration ranges from 1.8 to 63 times surface chlorophyll layers. It is likely that this subsurface layer contributes significantly to the overall primary productivity of Hudson Bay (Anderson and Roff, 1980). If phytoplankton are somewhat restricted to this layer because of nutrient limitations above and light limitations below, a deeper pycnocline may result in the entrainment of nutrients below the photic limits of these phytoplankton.

Additionally, other aspects of circulation may affect production. For example, if the pycnocline were to deepen (recalling that mixing generally occurs above the pycnocline), the large, unoxidized nutrient reserves of the lower levels of the bay, which normally take 4-14 years to turn over (Pett and Roff, 1982), might be brought to the surface more rapidly and increase the nutrient composition in the photic zone. The mixing, however, would occur in the fall or winter, the time when the pycnocline is deep (see Fig. 2). Although some species of epontic algae (unicellular algae associated with the lower interface of sea ice) photosynthesize at light levels as low as 0.01% of surface irradiance (Cota, 1985), it is not known whether the phytoplankton species in question have this ability. As well, the timing would not be characteristic of arctic waters, where a single peak of phytoplankton production normally occurs in the spring (Anderson and Roff, 1980).

The relative contribution of nutrients from James Bay to Hudson Bay is unknown. Preliminary budget calculations for the whole Hudson/James Bay system indicate that nitrate and total nitrogen contributions from deepwater mixing and land runoff are of the same order of magnitude. Nitrification appears to be a limiting factor in Hudson Bay; however, nitrification does occur in winter in the neritic (inshore regions) of James Bay (Pett and Roff, 1982). Levels of nitrate and nitrite in the surface ice and in the snow cover are generally a factor of two or three greater than those in the water immediately below the ice. It is therefore possible that melting ice and snow may be an important nutrient source during the spring phytoplankton bloom (Freeman *et al.*, 1982). In view of these processes and the probable large contribution of James Bay to Hudson Bay, withdrawal of the nutrients associated with the James Bay freshwater influx could severely affect the food chain.

Analysis of aperiodic phytoplankton blooms in Manitounuk Sound, a moderately saline (22‰) coastal embayment of southeast Hudson Bay, indicates that periods of destratification are not favourable for the phytoplankton species of the area. The destratification periods experienced appear to result from current (wind-induced) and tidal action and, although this upwelling provides required nutrients from below, it is the intermittent stable periods that are productive (Legendre *et al.*, 1982). The construction of a dam across James Bay could affect aperiodic phytoplankton blooms of coastal embayments in several ways. It could potentially decrease the stability of the water column of these localized embayments to a level too low to support production of the commonly associated phytoplankton species. As well, the dampening effect of James Bay on the tidal action of Hudson and James bays would be removed by the construction of the dam. The result might be an increase in tidal action and that associated with wind, which might increase the depth and frequency of aperiodic destratification. Waters may be less stable and the intermittent stable periods, required for production, might be reduced.

Long-distance and long-term effects are also possible. The freshwater contribution from James Bay is known to be a significant part of the total signal from the Hudson/James Bay system that is detected down the Labrador coast (Neu, 1982a; Sutcliffe *et al.*, 1983; P.A. Bolduc, Department of Fisheries and Oceans Canada, pers. comm. 1985). The strength of the signal may be affected because of a reduced circulation in Hudson Bay, and the salinity of its waters entering the Labrador current would be increased. The changes would be received at the Grand Banks in the autumn, the Scotian Shelf during the winter and Georges Bank probably during the spring. All these areas are productive fishing grounds.

The result of a reduction and/or the timing of the freshwater signal is not clear. If there is a reduction in a haline circulation system as previously described, then the potential for reduced productivity in these fishing areas is possible (Neu, 1975, 1982a,b). An alternate effect is inferred from a hypothesis that productivity increases farther south along the Labrador Coast because of the time required for a food chain to develop. This hypothesis is based on a nutrient input from a mixing area in Hudson Strait (Sutcliffe *et al.*, 1983) being advected south. An analysis of relationships between discharge, salinity and cod production suggest that in years of high freshwater outflow from Hudson Bay there is an increase in stratification and less upwelling and transporting of nutrients south, resulting in reduced productivity (Sutcliffe *et al.*, 1983). What has not been addressed in applying this hypothesis, however, is the potential effect of reduced nutrient input from Hudson Bay. Hudson Bay and Foxe Basin waters are estimated to contribute 37% of the Labrador Shelf water and are a major contributor to its high nutrient content (Sutcliffe *et al.*, 1983). If so, then a reduction in nutrient content from Hudson Bay, either directly or through the zone of mixing in Hudson Strait, has the potential to detrimentally affect productivity south along the Labrador Shelf. The one salient and consistent interpretation that is implied, however, is that there is some cause-and-effect relationship between the freshwater signal from Hudson/James Bay and productivity down the Labrador coast into the productive fishing grounds.

Aquatic Food Chain: Plankton and Macrobenthic Fauna

A reduction in the primary productivity of Hudson Bay would eventually decrease productivity at all levels of the food chain. Resource inventories are scant and the relationships among components of all levels of the food chain in Hudson Bay are poorly understood. For example, ciliates are found in high abundance at the Belcher Islands in southeast Hudson Bay. Although their role has not been adequately described in any ocean, it has been suggested that they do play a significant role in the food chain at the Belchers, where they serve as important predators on phytoplankton and as prey for the larger omnivorous zooplankton (Grainger, 1982). Of the 235 phytoplankton species found in Hudson Bay, 42 are freshwater species, reflecting the large freshwater runoff into the bay. Their ecological role and contribution to total productivity has not been adequately identified, although anadromous fish species are known to follow freshwater plumes out to the bay for feeding.

The distribution of macrobenthic fauna in river estuaries is linked to salinity and organic matter content in the sediments. Macrobenthic fauna populations will therefore probably change as a result of a reduction of freshwater at river estuaries, particularly in the estuaries of the southeast coast of Hudson

Bay, where salinity might increase the most. Such change will be a function of the mode of reproduction of the species, their physiological response to physio-chemical variations and the changes that will occur in the sediments. Species with a pelagic mode of reproduction will probably invade new habitats in the more saline waters of estuaries faster than species without such a mode of reproduction (Grenon, 1982).

Fish

There are approximately 60 species of fish found at present in the estuarine fish communities of Hudson Bay and James Bay. Latitudinal differences are found in the composition of the communities, with fewer species found in the north, where arctic and subarctic species are more prominent (Morin *et al.*, 1980). The adaptability of fish species to salinity changes will play a predominant role in determining the composition of estuarine fish communities of the Hudson Bay coast after dike construction (Ochman and Dodson, 1982). Considerable nearshore habitat would also be lost to marine species currently using this environment. There have been no scientific fish surveys of offshore James Bay and only one survey of offshore Hudson Bay, conducted in 1931. It is generally thought that the potential for a commercial fishery in either bay is low, although there has been some suggestion of potentially exploitable stocks of Greenland cod and capelin (Hunter, 1968).

A survey of fisheries potential for supplying feed for 5000 foxes at a fur farm in operation on the east James Bay coast is in preparation. Because of lack of support, the survey will be localized in the near-offshore of one village. Although fisheries potential in James and Hudson bays has not been studied, it is anticipated it would be negatively affected by the proposed scheme for the reasons outlined above and as a result of the anticipated reduction in primary production.

Impounding James Bay would have similar implications for ecological productivity in the newly formed lake. Virtually all marine organisms would be destroyed. Freshwater fish species presently dominant in Rupert's Bay are the most likely to dominate in the impoundment (Morin *et al.*, 1980; J. Dodson, pers. comm. 1985). However, additional problems might be anticipated, as experience has shown that newly created northern reservoirs are generally unproductive and fail to support viable commercial fisheries. In some small arctic lakes, a salt layer is found at depths resulting in a gradient so strong that the lower layer never mixes with the surface, loses its oxygen content and becomes unproductive. In addition, northern impoundments have been shown to release contaminants that may accumulate in fish tissues, rendering them unfit for human consumption.

The transfer scheme would also provide the opportunity for inter-basin transfer of exotic species north to south and vice versa. These could include plankton, bacteria, viruses, fish species and their associated parasites (e.g., lamprey) into the James Bay impoundment.

Mammals

Little information is available on marine mammals of Hudson Bay or James Bay. Ringed seals and bearded seals are the predominant seal species, and it is likely that they, as well as other marine mammals, would be negatively affected by a reduction in productivity at various levels of the food chain. Ringed seals require fast ice for breeding, whereas bearded seals

are usually associated with moving pack ice and shallow banks, which are free of land-fast ice in the winter (Mansfield, 1968). Changes in ice pack regimes may affect either or both species. Ringed seals are found on all coasts of both Hudson Bay and James Bay, where their populations have been estimated at 455 000 and 61 000 respectively (Department of Fisheries and Oceans Canada, 1985). The only population estimate for bearded seals is a 1958 figure of 84 000 in Hudson Bay (Mansfield, 1968). Smaller populations of harbour seals, which require ice-free conditions in the winter, occur sparingly at isolated localities along all coasts, while small numbers of harp seals are found as far south as the Belcher Islands in the summer. Again, changes in the ice pack, notably a reduction of open water, could result in a reduction of their population. Walrus population estimates in the eastern Canadian Arctic are incomplete. In Hudson Bay the main concentration is at northeastern Coats Island and southeastern Southampton Island, where they are found during all seasons, with an estimated summer population of 2000. In the 1950s and 1960s the walrus population of Foxe Basin and Hudson Bay together was estimated at 8500. They were found on both coasts of Hudson Bay and as far south as the Belcher Islands (Reeves, 1978).

Polar bears are directly dependent on seals as their main food source and would be affected by any long-term changes in seal populations. The large numbers of polar bears found on the coasts of Hudson Bay and northern James Bay during the summer and fall and on islands in northern James Bay could lose important denning areas due to flooding and construction. In particular, areas around Cape Henrietta Maria, which is a likely candidate site for dike construction, support a large population of polar bears (Prevett and Kolenosky, 1982).

White whales (also known as belugas) are the main species of whale found in Hudson Bay. The most recent report estimates that a population of 8000-9000 belugas summer in western Hudson Bay and winter in open areas of Hudson Strait and Ungava Bay (Finley *et al.*, 1982). Other evidence suggests a portion of the population uses the polynya of northwest Hudson Bay and James Bay in winter (Jonkel, 1969; Sergeant, 1973). Additionally, a small population of a few hundred, reduced from an estimated historical population of 5000, spend the summer on the east coast of Hudson Bay (Finley *et al.*, 1982).

Estuaries appear important to belugas, serving as feeding grounds, areas for as yet unexplained social behaviour and calving grounds (Sergeant, 1973). It is hypothesized that the higher water temperatures of estuaries may lessen the shock of birth and reduce heat loss in the first few days after birth until sufficient subcutaneous fat has been acquired. Loss or alteration of estuaries, which appear to be traditionally used, could further affect whale behaviour (i.e., migration pattern), reproductive success or both. At present there is considerable concern for the beluga populations because of continued harvesting and because of effects of present hydroelectric developments. As the distribution and movements of belugas are greatly influenced by ice conditions (Finley *et al.*, 1982), changes in ice pack regimes may have significant consequences. In conjunction with the possibility of lower water temperatures, a reduction in circulation of Hudson Bay could threaten the existence of polynyas. A reduced circulation could also reduce the upwelling of nutrients that occurs in the northwest of Hudson Bay, an area that appears biologically important for other marine species as well. A closing of open areas would be disastrous for any non-migratory populations of marine mammals.

An endangered population of possibly less than 100 bowhead whales inhabits northern Hudson Bay, most probably on a year-round basis, although once again data are limited. This Hudson Bay/Foxe Basin population is known to summer near Southampton Island in the same northwest area as the beluga whales, although possibly displaced a little north because of competition. It is not known whether the whole summer population winters in Hudson Bay, but sightings have been made near Southampton Island, in the Foxe Basin shore leads and polynyas and in the dense shifting pack ice of northeast Hudson Bay and west Hudson Strait (Reeves *et al.*, 1983; McLaren and Davis, 1982).

A strong circumstantial argument suggests that ice conditions affect the survival of bowhead whales. An increase in ice cover could increase the possibility of entrapment in the ice, as bowheads tend to remain near the edge of ice and would restrict their movement to preferred feeding grounds (Mitchell and Reeves, 1982). An increase in ice cover and a decrease in productivity in the food chain would not be beneficial to the population's present tenuous existence.

Waterfowl, Shorebirds and Seabirds

The Hudson Bay and James Bay coasts are a major migration pathway for many species of geese and ducks en route between breeding and wintering areas. Approximately 2.5 million lesser snow geese and 200 000 Canada geese (Thomas and Prevett, 1982) use staging areas on the coastal marshes of the Hudson Bay lowland during spring and fall migration. In an average year, 1.5 million of the lesser snow geese use the James Bay coastal areas (Prevett *et al.*, 1979). The high fertility and productivity of the coastal zone support a wide range of food species, which enable reproduction, growth of juveniles and fattening of all ages prior to the fall migration (Kerbes, 1982). In the spring, lesser snow geese and Canada geese are able to maintain weight for the final migration to their breeding areas by feeding on early exposed new growth and the perennating organs of arrowgrass. A major breeding colony of lesser snow geese is located just west of Cape Henrietta Maria, with smaller breeding areas located on Akimiski Island near Churchill and in the vicinity of Eskimo Pt., N.W.T. (see Fig. 1) (Thomas and Prevett, 1982). Approximately 75% of the Atlantic brant goose population is concentrated on the eel grass beds of the Quebec coast and parts of the Ontario coast of James Bay (Thomas and Prevett, 1982), and almost the whole North American population of black scoters, numbering up to 320 000 in the fall, may stage in southern James Bay (R.K. Ross, Canadian Wildlife Service, pers. comm. 1985). Additionally, many other species of waterfowl use the inshore intertidal and brackish coastal habitats, which are very susceptible to changes in salinity. Major species include black duck, pintail, mallard, wigeon, green-winged teal and scaup. Mergansers and loons make extensive use of offshore waters for feeding and significant numbers of common eider spend the winter in James Bay. Although spring migrants use the southern James Bay shoreline the most heavily because it is the first section to melt, the coast of Hudson Bay is also used (Ross, 1982; R.K. Ross, Canadian Wildlife Service, pers. comm. 1985).

Probably the entire Hudson Bay population of Hudsonian godwits use staging areas on the west coast of both bays to accumulate fat reserves essential for their direct flight to South America. They, as does probably the entire North American

population of red knots (R.I.G. Morrison, Canadian Wildlife Service, pers. comm. 1985), use the lower intertidal zone, which would be destroyed in James Bay and possibly severely altered in Hudson Bay by the proposed project. Both are species for which there is a considerable conservation concern at present. Other important species include dunlin, black-bellied plover, golden plover, semi-palmated plover, greater and lesser yellowlegs, sanderlings, four species of sandpiper, whimbrel and marbled godwit. The coasts of both bays are also used by the nearly extinct eskimo curlew. Effects of dike construction would almost certainly be negative, particularly in James Bay (e.g., delayed ice breakup, lower productivity of marshes and invertebrates and alteration of seasonal resources). This could result in the destruction of all or a substantial portion of many North American migratory bird populations (D. Welsh, Canadian Wildlife Service, pers. comm. 1985).

The area of northern Hudson Bay and west Hudson Strait supports the third largest seabird population in the Canadian Arctic, dominated by the thick-billed murre (Gaston, 1982). The absence of other common species and the rapidly fluctuating population of the murre suggest a delicate balance of food supply and population size (Gaston, 1982). A reduction in food supply, one possible effect of terminating the flow of James Bay, might seriously affect the murre population. Again, further study of oceanographic processes and their effect on food reserves is needed.

ADDITIONAL EFFECTS AND CONCERNS

“James Bay may be interpreted as a sediment sump for the centre of the continent” (Kranck and Ruffman, 1982:359). Rivers are estimated to bring 4.12×10^7 tonnes of sediment per year into James Bay (Kranck and Ruffman, 1982). Although this would only form a 0.33 mm layer if distributed evenly over the whole bay, the dam construction could alter the present patterns of sediment deposition, complicating engineering processes of water transfer, and affect water quality and aquatic life within the embayment. With a removal of estuarine circulation it is likely that coarse suspended particles would tend to settle out of the water column sooner, resulting in the formation of river deltas. In contrast, the very fine sediments would tend to stay in suspension longer because a freshwater regime would result in less flocculation and precipitation (K. Kranck, pers. comm. 1985). Potential effects could be a reduction in primary productivity as less light becomes available and an increased potential for clogging gill and filtering mechanisms of aquatic organisms (e.g., fish gills).

Although engineering plans are still speculative, estimates indicate that over one billion m^3 of landfill will be required to construct a dike across the opening between James and Hudson bays (Bruneau, 1985). The source of this landfill has not been identified, but the removal of such quantities is certain to have some detrimental impacts.

The transfer scheme itself could have severe implications for fisheries resources by restricting the movement of fish with dams and the possibility of entrainment and death of juvenile fish at pumping facilities, particularly at the James Bay source. Potential flooding along river valley corridors used for the water transfer would be accompanied by direct biological impacts and social disruption.

DISCUSSION

Modelling of partial diversions of James Bay's freshwater

budget and modelling and examination of water diversion projects and analogous situations elsewhere have raised the concerns of possible long-term ecological, oceanographic and climatic effects as a result of the GRAND Canal scheme. Due to an inadequate database and cause-and-effect relationships that are poorly understood, questions concerning possible major changes to the arctic ice pack and its effect on atmospheric circulation, temperature and precipitation patterns over the northern hemisphere cannot be adequately answered at this time. Theory and models, however, do indicate that there would most likely be local modifications, probably regional modifications and possibly large-scale changes.

Playing a central role and of prime concern is the potential for changes to the depth and seasonality of Hudson Bay's pycnocline. It is possible that due to the diversion of James Bay's freshwater component, ice formation in Hudson Bay would be increased as the shallow surface pycnocline of Hudson Bay would form earlier in the spring and deepen in the summer (Prinsenberg, 1983). In conjunction with a removal or reduction of the warm freshwater outflow from James Bay in the spring (Prinsenberg, 1984, 1986b), the breakup of ice in Hudson Bay could also be delayed. Although these changes indicate a general cooling of the sea surface layer, the implications this may have for large-scale climate modification is still unknown. It has been suggested, however, that atmospheric interactions may be able to reduce some climate changes that might be expected as a result of ice pack modification (Prinsenberg and Danard, 1985).

A second cause for concern in modifying the depth and seasonal regime of the pycnocline is its role in primary productivity. Although also incompletely understood, the pycnocline may be inextricably linked to the periodicity of nutrient upwelling and the spring phytoplankton bloom (Anderson and Roff, 1980; Pett and Roff, 1982). A deepening and seasonal delay in the pycnocline's development could result in a reduction in primary productivity. Additionally, the spring phytoplankton bloom may be further reduced by delaying or removing the nutrient influx that generally accompanies the melting ice in the spring (Freeman *et al.*, 1982).

Aperiodic phytoplankton blooms may also be reduced in frequency and intensity as a functional response to the physical barrier of the dike itself. Loss of the dampening effect of James Bay on tidal and wind action in Hudson Bay would likely result in fewer intermittent stable periods, which are required for phytoplankton production (Legendre *et al.*, 1982).

A reduction in primary productivity will have relatively obvious effects on productivity up the food chain within Hudson Bay, affecting fish, seals, polar bears and whales. As well, there would likely be some less obvious effects on productivity downstream. There appears to be some interaction between the freshwater signal from Hudson Bay and productivity down the Labrador Coast (Neu, 1975, 1982a,b; Sutcliffe *et al.*, 1983), but the relationship between the nutrient contribution of Hudson Bay to the zone of mixing in Hudson Strait (a zone that supplies nutrients for the productive Labrador Shelf water) has not yet been properly addressed. Extrapolation of nitrate, salinity and temperature data have indicated that Hudson Bay and Foxe Basin outflow may account for 37% of the Labrador Shelf waters and that they are a major contributor to its high nutrient content (Sutcliffe *et al.*, 1983). A reduction in this nutrient contribution could be detrimental to the Labrador Shelf fishing industry.

Resource inventories of many biological entities that may be affected are also incomplete, although it is quite clear that a major portion of the North American migratory bird population would be negatively affected. Virtually millions of waterfowl and shorebirds depend on either the James Bay or Hudson Bay coast as staging areas during periods of migration in the spring and fall. Lower productivity of coastal marshes, due to changes in nutrient input, salinity and temperatures and/or alteration to their seasonality, could result in destruction of all or a major portion of the North American migratory bird population.

Changes in ice pack regimes would also affect marine mammals. Beluga and bowhead whale populations are thought to utilize open areas of water close to broken ice flows and polynya. The projected changes could potentially increase fast ice and pack ice and close polynya known to be biologically productive areas (Stirling, 1980). Besides detrimentally affecting whale species, one would expect a shift in the ratio of fast to pack ice to be reflected in a shift in the ratio of ringed seals to bearded seals respectively. The interrelations between productivity (food source), habitat, predators (polar bears) and population regulation of seals are not yet established.

This analysis of the potential ecological effects of the GRAND Canal project indicates that a great deal more research is warranted before such a large-scale diversion is seriously considered. The implications for some of the ecological parameters addressed suggest that large-scale, possibly irreversible detrimental changes to the northern ecosystem would result. Downstream effects, which receiving areas of the diversion may encounter, have not been addressed but also need to be studied.

Specifically, more oceanographic research in Hudson Bay, particularly documenting pycnocline development and its role as a regulator of sea surface temperature, ice pack and primary productivity, is needed. The relationship involving circulation and exchange between Hudson Bay, Foxe Basin, Hudson Strait and the Labrador Sea with respect to freshwater contributions and nutrient exchanges must be established. As well, more complete biological inventories and an understanding of their ecological relationships are needed in all potentially affected bodies of water.

These are all complex questions for which long-term monitoring will be necessary in order to establish relationships of ecological parameters through the total range of variability that could be experienced naturally. In particular, data at the limits of the range of variability will be helpful in modelling responses to conditions as extreme as envisioned in the GRAND Canal scheme.

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