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See table of contents

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Article abstract

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Articles

Fundy Tidal Power: Environmental Sedimentology

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Summary
Tidal power potentially can contribute significantly to North America's future needs. Proposed developments in the upper reaches of the Bay of Fundy have a total generating capacity half again that of Niagara Falls. Construction of tidal power barrages could, however, have serious consequences to the marine environment. The high productivity of the intertidal communities in the upper reaches is maintained in part by tidal flushing; these communities are also affected by changes in sediment type. The upper reaches are important feeding areas for migratory shorebirds and commercial species of fish, and may function as a nursery estuary, supporting offshore fisheries. Serious siltation problems could also shorten the lifespan of tidal power barrages. It is questionable whether studies now underway to assess the consequences of development can gather the necessary data within the allotted time frame. Computer simulation of sediment dynamics combined with programs designed to assess the effect of siltation on benthic communities will, probably within a year, allow estimates of expected productivity losses to be made for some of the areas which have already been studied.

Introduction
Urgent need for renewable energy sources has prompted interest in harnessing the tides. Macrotidal coastlines considered as possible areas for development of tidal power projects occur in Argentina, Australia, Britain, Canada, France, India, Korea, Russia, and the United States. In North America, the most suitable areas for possible exploitation of tidal power are the Gulf of Alaska, Ungava Bay, and the Bay of Fundy. Of these areas, plans are furthest advanced for the Bay of Fundy.

Recent study of power potential of the upper reaches of the bay of Fundy began in 1966, with formation of the Atlantic Tidal Power Programming

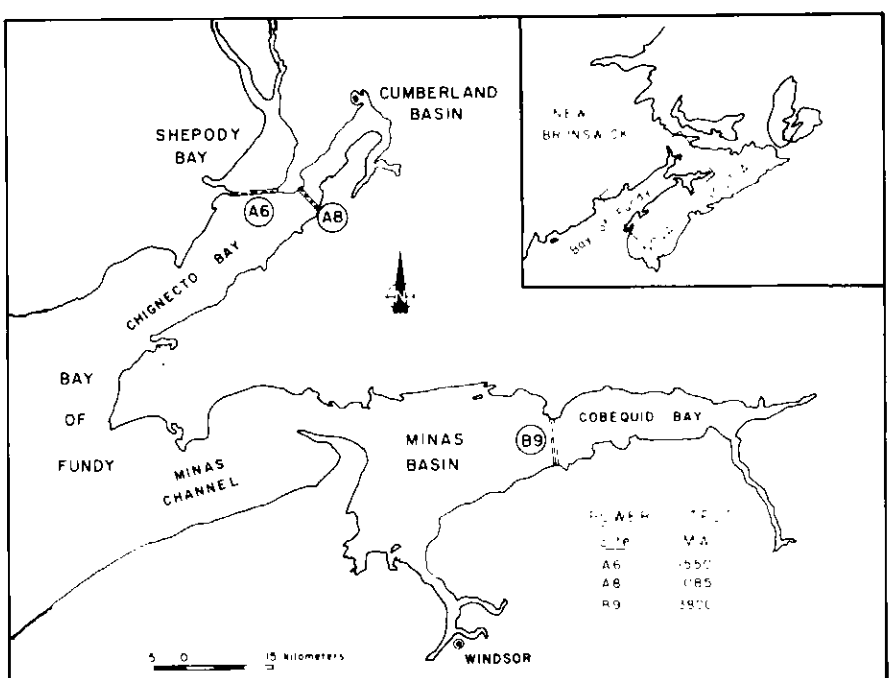

Figure 1
The upper reaches of the Bay of Fundy, showing the location and the proposed output of the three most-favoured sites for tidal power projects. The Cumberland Basin A8 site is currently the preferred candidate

Board, financed by the Governments of Canada, Nova Scotia and New Brunswick. The study considered a large number of possible sites, and selected three for detailed study: A6 in Shepody Bay, A8 in the Cumberland Basin, and B9 in the Minas Basin (Fig. 1). The final report concluded that power from these sites was technically feasible, but not economic at the time (1969). It recommended that the question be re-examined should capital costs or interest rates decline, or should energy costs rise, due to increases in the cost of imported oil or to environmental restrictions on the operation of fossil-fueled plants.

The early 1970s brought dramatic increases in the price of fossil fuels. In 1972, the Governments of Canada, Nova Scotia and New Brunswick appointed the Bay of Fundy Tidal Power Review Board to monitor the situation. In 1975, a study was financed to oversee further developments. This study was divided into Phase I, preliminary engineering studies and site selection, and Phase II, engineering design, modelling, and socio-economic and environmental studies. At the end of each phase, there was to be a "go" or "no-go" decision made as to whether to proceed. A "go" decision following Phase II signals the beginning of plant design and construction.

Phase I was completed in November, 1977; the decision was "go". The A8 (Cumberland Basin) and B9 (Minas Basin) sites showed favourable benefit-to-cost ratios; the A8 site was the preferred candidate because of socio-economic considerations, and because, as the project is much smaller than B9, any environmental problems should be minimized. The A6 (Shepody Bay) site was deemed uneconomic at present, but any increase in the price of fossil fuels more rapid than the general rate of inflation would prompt re-examination of this project.

The possible contribution of tidal power is far from minor. Proposed installed generating capacities of the A6, A8 and B9 sites total 6,400 megawatts; the A6 site is roughly equivalent to two CANDU nuclear reactors. Total proposed capacity of the three sites is about three times Canada's total installed nuclear generating capacity as of early 1976; in more readily-understandable terms, about half again the total hydro-electric contribution, to both Canada and the United States, of Niagara Falls.

Stated advantages of tidal power are that it is clean and renewable, and costs of generation remain relatively constant with time. One disadvantage is that of timing; maximum power generation will frequently occur during off-peak hours, depending on the tides. Some means of storing power will be necessary. Proposed schemes have included pumped storage in small, high-head reservoirs, compressing air in underground caverns, and on-site generation of hydrogen.

Little marine research has been done as yet in Chignecto Bay. Much more is known about the Minas Basin, proposed site of the large B9 project, where research by the Atlantic Geoscience Centre and McMaster University has been under way since the early 1970s. Some results of this research suggest that tidal power developments in the upper reaches of the Bay of Fundy may have consequences to the marine environment which were either

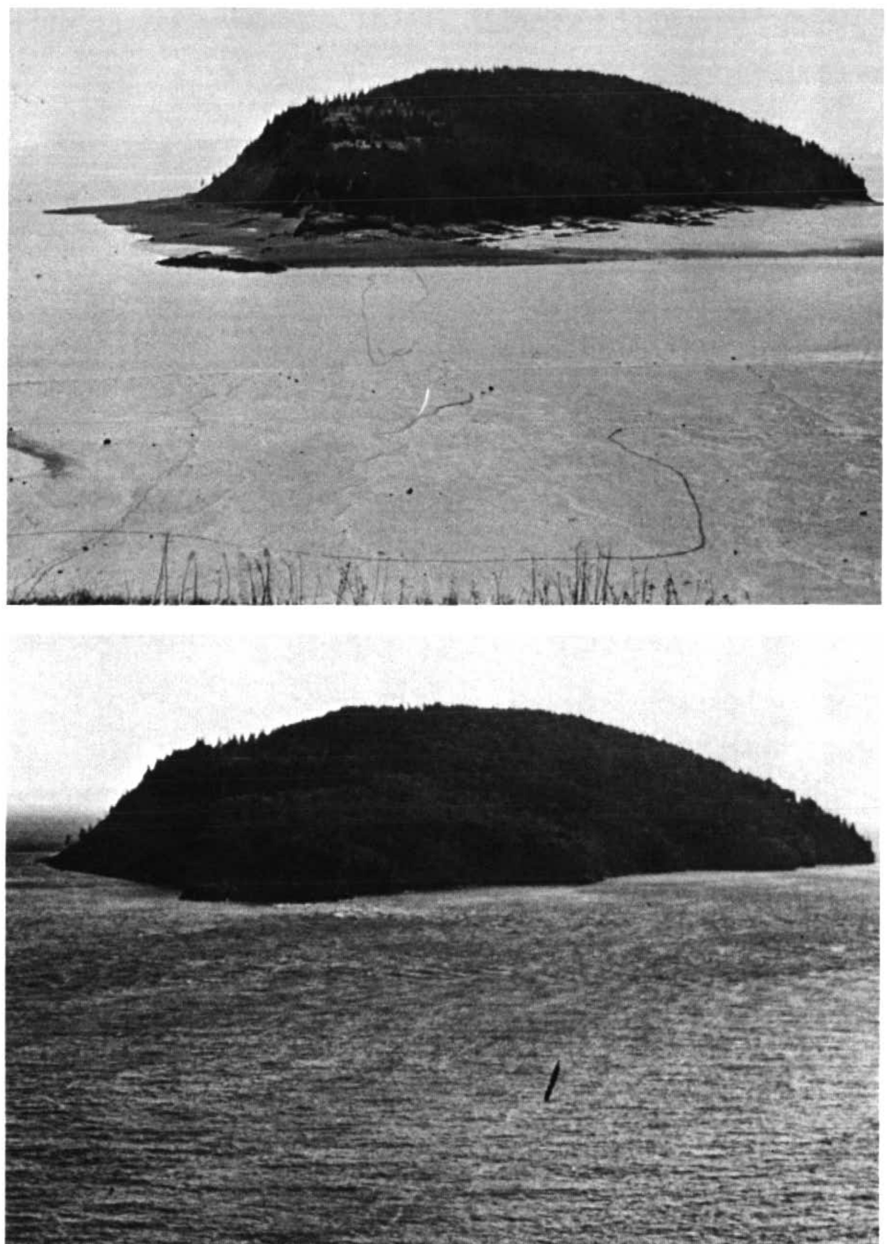

Figure 2
Low tide (top) in the region of Five Islands, Nova Scotia; high tide (bottom).

overlooked or underestimated by earlier studies.

Physical Setting and Processes
The upper, easterly arm of the Bay of Fundy bifurcates into two main portions: the Minas Channel and Basin, in Nova Scotia, and Chignecto Bay, bordered by Nova Scotia and New Brunswick. Chignecto Bay in turn is divided into Shepody Bay, to the north, and the hook-shaped, easterly-directed Cumberland Basin. The Minas Basin, Shepody Bay and the Cumberland Basin are termed the upper reaches of the Bay of Fundy: these areas record the highest tides measured anywhere in the world. Tidal maxima of 17 m occur in Cobequid Bay, the eastern section of the Minas Basin.

These extreme tidal ranges expose extensive intertidal sand- and mudflats, some of which exceed two km in width (Fig. 2). Area of the intertidal zone is about one-third the total marine area in the system.

Water masses in the upper reaches vary markedly from those in the Bay of Fundy proper. In the Minas Basin, salinities are lower, temperature fluctuations greater, and the water column is vertically well-mixed (Amos and Joice, 1977). The most important difference is the extreme turbidity of the water throughout the system. Shorelines in the area are generally composed of Carboniferous slates, friable Triassic redbeds and easily-eroded Pleistocene tills and Holocene soils. Shoreline recession rates of up to two m per year have been measured in the Minas Basin (Amos, 1977), representing a major source of sediment input to the system. This sediment is kept in suspension by strong tidal currents, up to 50 cm per second over some sand bars. Suspended sediment concentrations of several hundred ppm commonly occur in nearshore zones of the Minas Basin (Amos, 1977), and values as high as 400 ppm have been measured (Risk and Moffat, 1977). Overall sediment transport in the Minas Basin is eastward, toward the head of the bay.

Much of the intertidal zone in Minas Basin is occupied by sand with large, mobile bedforms (Dalrymple *et al.*, 1975). Thick mud accumulations occur in sheltered areas, and mud veneers occur on and intermittently suspended over the sands. Sediments in Shepody Bay and the Cumberland Basin are considerably finer-grained, and it is possible that concentrations of suspended sediment are even higher than those recorded for the Minas Basin.

Marine Ecology of the Upper Reaches
Intertidal flats of the upper reaches of the Bay of Fundy support high density, low diversity assemblages of largely deposit-feeding invertebrates, very similar to Petersen's (1924) subtidal "*Macoma balthica* community", which occurs in many parts of the boreal Atlantic. The major contrasts between assemblages in the upper reaches and similar assemblages throughout the boreal and temperate Atlantic are quantitative: densities and biomass values are astonishingly high, in excess of most values recorded in the literature. Species diversity on these flats is among the lowest ever reported (Fig. 3). This low diversity may be partly explained by the extreme physical conditions. Organism mortalities occur as a result of extreme tidal fluctuations, storms and hurricanes, the effect of ice rafting and erosion and predation (Craig, 1977, Craig and Risk, 1976, Yeo, 1978, Yeo and Risk, 1979).

Notwithstanding this catstrophic picture of life on the mudflats, however, very high rates of secondary productivity are maintained. Maximum organism densities occur on the lower mudflats; the upper mudflats, near high tide mark, contain somewhat fewer organisms, while the outer sands are relatively barren. Data from Minas Basin suggest that the upper reaches are rimmed with narrow zones of extremely high benthic productivity. How is this productivity maintained, and what is its importance?

The accepted picture of the trophic dynamics of many estuaries involves tidal flushing of detritus from salt marshes, combined with phytoplankton productivity in the open water. Marshes around the upper reaches are not extensive; where these marshes have been studied, primary productivity was found to be low, relative to other marshes along the Atlantic coast. Carbon input during late winter and early spring by ice rafting of marsh detritus and stream transport of terrestrial detritus is likely not a major source: values of sedimentary organic carbon on the Minas Basin flats are low, relative to other estuaries, and reach maximum values in late summer. Phytoplankton contribution is probably also minor, because of the turbid water. Zooplankton from the Minas Basin have depleted

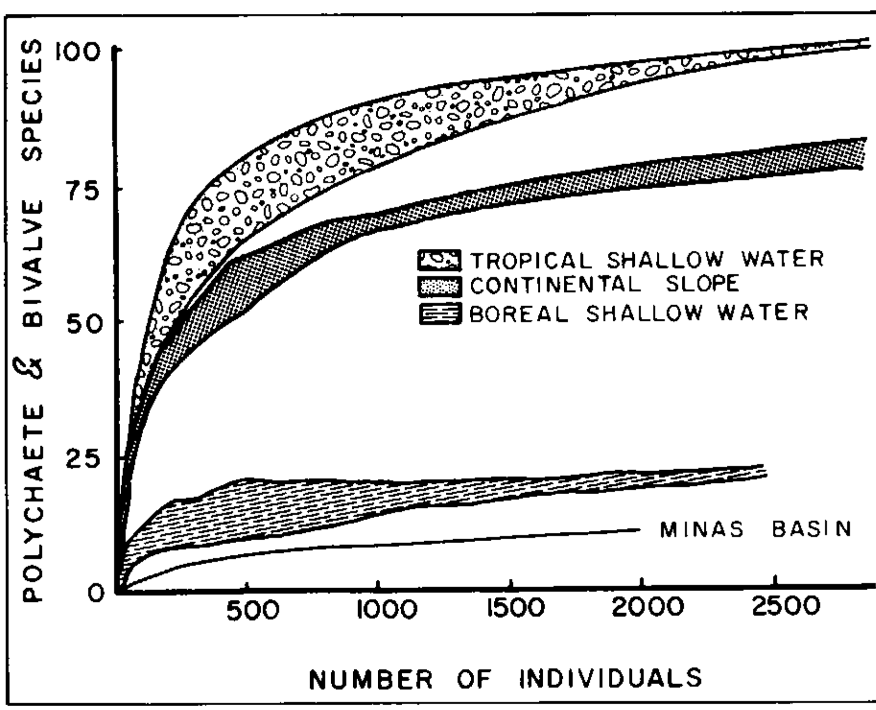

Figure 3
Sanders-type species rarefaction curves for the benthic fauna of the Minas Basin, compared with other marine habitats. The faster the curve for a given habitat rises, and the higher the final level attained, the more diverse the habitat. It can be seen that the Minas Basin exhibits very low species diversity.

fat reserves, surface water samples show Chlorophyll "A" values so low as to be almost undetectable, and Land Sat imagery suggests year-round low values of Chlorophyll "A" in surface waters (T. Stewart, pers. commun.). It is likely that primary production by benthic microflora on exposed tidal flats represents a major carbon input. Stable isotope analyses suggest that the majority of the organic carbon on the flats is derived from algae. Diatoms and bacteria form an important component of the diet of the deposit-feeders.

The intertidal flats of the upper reaches of the Bay of Fundy probably represent a unique ecosystem, differing from similar areas in Britain, Holland, Germany and the United States both quantitatively, (higher organism densities and secondary productivity values, lower diversities) and qualitatively (relative importance of the carbon sources). An explanation for the character of the upper reaches may lie with the only unique feature of the environment: the extreme tidal range. Tides do a good deal of "biological work", transporting nutrients, larvae and dissolved oxygen, and removing waste products. Water samples from the Minas Basin show that maximum flood and ebb currents are associated with a near-bottom "slug" of highly turbid water, in which values of organic carbon and nitrogen are very high (Risk and Yeo, in press). The high carbon values are due to pickup of benthic algae, and to resuspension of fecal and pseudofecal deposits, a significant input of suspended particulate matter and a major pool of organic carbon. For example, based on estimates of the amount of excreta produced daily by the total *Macoma balthica* population in Minas Basin and the organic carbon content of these excreta, there are about one and one-half metric tons of carbon, each day, tied up in mobile, easily-transported biodeposits. Without breakdown and recycling driven by tidal flushing, this carbon would be unavailable to the benthos.

The potential importance of high intertidal productivity in the upper reaches lies in the relatively large area of the intertidal zone, perhaps as much as one-third of the total area. Subtidal habitats in the Minas Basin generally consist of a gravel lag, in which values of organic carbon range from low to undetectable (B.F. Long, pers. commun.). Bottom photographs show some epizoan growth, but benthic macroalgae are absent. Core data indicate lack of an infaunal community in central and eastern Minas Basin. Evidently, the majority of the benthic invertebrates reside in the intertidal zone. Should the organic carbon produced intertidally remain within the system, to be either metabolized or buried within the sediments, then this ecosystem would be of academic interest, with little effect on the Bay of Fundy-Gulf of Maine system. Little or no organic carbon, however, is accumulating on the floor of the Minas Basin, and little carbon is being buried in the sediments anywhere within the upper reaches. There is ample evidence that carbon from the flats is being exported through the feeding activities of vertebrates: birds, fishes, and humans.

Birds, Fish and Fisheries

"The upper Bay of Fundy is probably the most important area in eastern North America" for migratory shorebirds (Morrison, 1977, p.187). These birds stop over to feed on the intertidal flats, and build up their fat reserves for the long flights to their wintering areas in South America. Groups of shorebirds begin to arrive in mid-July; individual groups may remain in the area only a few weeks. There is continual passage of shorebirds through the feeding grounds from mid-summer to early September. Large numbers of waterfowl (mainly Canada Goose, Black Duck, eiders and scooters) pass through the area in March-April, and again in early fall.

It is difficult to estimate the total number of birds using the upper reaches. Aerial surveys have identified major concentrations of shorebirds in Shepody Bay, the Cumberland Basin, the southern bight of the Minas Basin and the southern coast of the Minas Basin. Mary Point, New Brunswick, is probably the single most important site for Semipalmated Sandpipers in eastern North America. An aerial survey of the upper reaches on July 29, 1976, estimated more than 550,000 shorebirds (Hughson, 1977); throughout the summer, it is possible that as many as five million shorebirds stop over.

Birds roost inland, and begin to appear over the shore in pods of several hundred to several thousand as the tide falls. The small, scavenging amphipod *Corophium* is the main prey species, although gut contents also show nereid polychaetes and *Macoma* shell debris. There is indirect evidence, from *Corophium* population monitoring and size-frequency data, that bird predation significantly reduces *Corophium* during July and August.

Fish feed during high tide on the same flats that the birds use during low tide. Feeding pits made by predatory groundfish are very common, and evidence of feeding by rays and sturgeon also occurs. In all, over 40 species of fish have been found in the upper reaches, many of them economically important. Bottom feeders (flounder, sturgeon, cod, tomcod, skates and rays) prey primarily on benthic invertebrates. Small fish feed mostly on *Corophium*, while large fish consume *Macoma* and nereid worms. The sand shrimp, *Crangon septimspinosa*, breeds in the subtidal, and occurs both there and on the tidal flats. *Crangon* is a major element in the diet of a large number of fish species.

Pelagic feeders, such as salmon, shad, mackerel and hake, consume baitfish or juvenile fishes, which in turn feed largely on the intertidal flats.

In addition to adult representatives of economic fish species, the upper reaches also support huge numbers of juveniles. Field workers frequently report seeing large concentrations of juvenile (2 to 4 cm) flounders during summer, trapped in shallow pools. Juvenile eels are also common in summer, as are the larvae of several economoically-important species. Anadromous fish (salmon, striped bass, shad) spawn in several of the rivers draining into the upper reaches.

Commercial fisheries presently operating in the upper reaches are not very extensive. Salmon and shad are taken in the Petitcodiac River and Shepody Bay, and a single weir in the Cumberland Basin takes several species (David Scaratt, pers. commun.).

About a dozen species are taken in the Minas Basin. In recent years, the landed catch has been about three million pounds, worth about $400,000. The major species of value are winter flounder, herring, alewives ("gaspereau"), shad, and striped bass; smaller amounts of salmon, cod, and halibut are also taken. Clamming (for *Mya arenaria*) is very active; the Economy Point-Five Islands area supports up to 75 commercial diggers, and there is intensive recreational clam digging throughout the area.

Although the upper reaches were classified as unproductive many years ago (Huntsman, 1952) and are not heavily fished at present, it is likely that fish stocks in these waters are greatly underutilized, due to the difficulties involved in operating boats. Experimental seining operations in the Minas Basin have yielded large catches of fish.

The main importance of the uppper reaches to fisheries probably lies in their possible function as nursery estuaries. The importance of estuaries as spawning and rearing grounds for commercially-important fishes has been emphasized in many previous studies (for example, Odum, 1971). It is certainly possible that the upper reaches, with their observed high secondary productivity, could be exporting carbon not only in the form of fat birds, but also as juvenile fishes. The extent to which the upper reaches support offshore fisheries of the Bay of Fundy-Gulf of Maine system, and perhaps even Georges Bank, has yet to be determined.

Possible Impacts of Tidal Power

Although the precise nature of the impact on the marine environment of construction of tidal power barrages is impossible to predict at this time, general evaluation of the impact is a problem in applied sedimentology. Reduced circulation following barrage construction will probably result in sand deposition around the barrage and in the channels, transient and/or permanent mud deposition on the intertidal flats, and a reduction in the efficiency of flushing by tidal currents.

A possible analogue of the effects of barrage construction exists near Windsor, Nova Scotia (Fig. 4). Construction in 1970 of a small rock-filled causeway across the Avon River has reduced circulation up the Avon estuary, and created a mudflat seaward of the causeway which contains about two million cubic metres of sediment. This mudflat has accreted vertically more than four m in five years; accretion rates of more than 14 cm per month have been measured (Amos, 1977).

Preliminary data suggest profound differences between the Windsor mudflat and normal mudflats. Although the sediment grain size distribution on the Windsor flat is comparable to other intertidal flats in the upper reaches, organism assemblages are different: *Mya arenaria* is absent, species diversity is lower, and total density and biomass are reduced. This represents an important depletion of the total prey available to fish and birds. Winter observations indicate considerable disruption of the surface of the Windsor flat by ice, which may partly account for the reduced densities and biomass.

Altering sedimentation patterns due to construction of a tidal barrage could affect distribution patterns of invertebrates due to high water content of the newly-deposited sediments.

The relatively low values of organic carbon in the sediments throughout the upper reaches, coupled with the high organism densities, suggest that the system works very efficiently, driven by tidal flushing. Reduction in the strength of tidal currents might, therefore, cause a reduction in total productivity. Consequently, the rate of biological 'recovery' of the system will be a function of the rate at which rapidly-deposited sediments dewater to allow re-establishment of the normal fauna, and the rate at which the benthic organisms can respond to changes in sediment distribution.

Of primary economic concern is the rate at which a tidal power barrage would silt in so as to become unusable; earlier projections of barrage life may have been overly optimistic. Using Windsor as a model, we can predict that barrage construction will cause widespread deposition of sediments. Siltation due to causeway construction at Windsor has occurred as far away as 20 km from the causeway site. Sediment loading could result in catastrophic mortalities of the soft-shelled clam, *Mya arenaria*, which is unable to tolerate rapid siltation.

Construction of tidal power barrages might also affect the physical oceanography of the whole Bay of Fundy-Gulf of Maine system. The general picture, from computer modelling studies, is a drop in tidal amplitude at the barrier, and an increase in tidal amplitude away from the barrier (Greenberg, 1977). Initial computer simulations suggested that the tidal amplitude at Boston would be increased as much as half a metre (which prompted the suggestion, at one of the earlier workshop discussions on tidal power, that electricity could be sold to the citizens of Boston to enable them to pump out their basements). Subsequent refinements of the model indicate an increase, at Boston, of only a few centimetres. Possible influences on upwelling patterns in the outer Bay of Fundy have yet to be assessed.

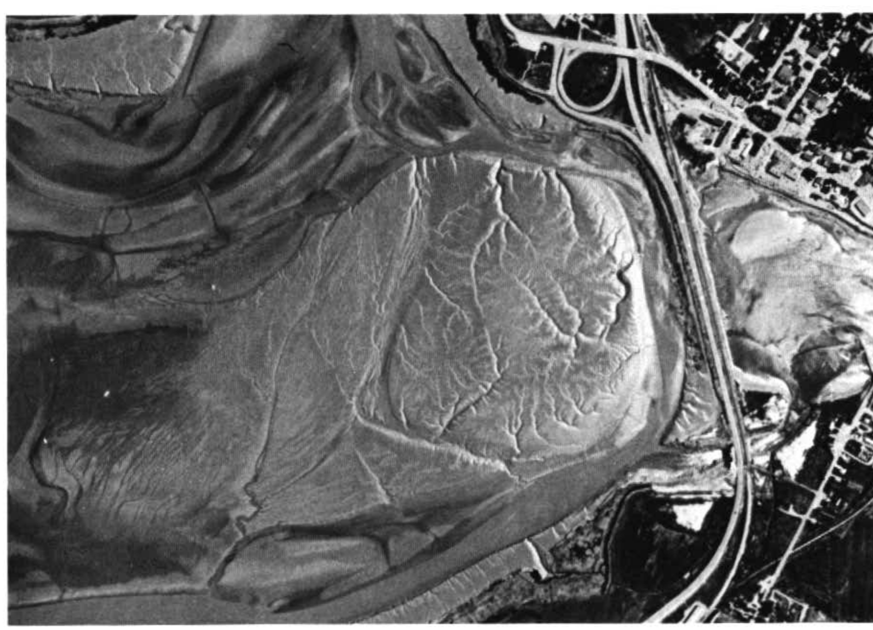

Figure 4
Air photograph of the mudflat near Windsor, Nova Scotia, created by construction of a solid rock causeway (highway at bottom for scale). Conditions on this mudflat are believed to be analogous to the effects of tidal power developments.

Discussion

Any major construction project involves tradeoffs between economic gains and environmental impacts. Tradeoffs associated with the possible alternative power sources for the Maritimes: nuclear, coal - and oil-fired thermal, are fairly well known. We are now able to identify some of the specific effects of Fundy tidal power development, although the magnitude of these effects has yet to be assessed. There is clearly a potential for altering oceanographic and ecologic conditions in coastal waters of both Canada and the United States. There are, however, possible benefits to the United States. The Maritime Integrated System can absorb the substantial energy contribution from the Cumberland Basin (A8) site. Further development, particularly of the Minas Basin (B9) site, would allow considerable energy export to the New England Power Pool (Anon., 1977). Before an informed decision can be made, citizens of both nations should be aware of the consequences and alternatives. An environmental assessment and review process has been set in motion by Environment Canada, which is to include public hearings in communities in the Maritime provinces.

The pre-investment design program now underway will involve the establishment of a data base, regime modelling, engineering and system design, and a smaller amount of funding for socio-economic and environmental studies, plus continuing investigations at other sites. This phase is scheduled to be completed in mid-1981. During this relatively short time span a considerable body of information must be gathered. Work is now underway in Chignecto Bay to collect basic data on physical oceanography, sediment transport and the carbon budget. A project involving rates of recolonization of newly-created mudflats is underway in Minas Basin, and smaller projects have been mounted at other localities by a variety of institutions. As yet, no studies are planned to specifically assess the contribution of the upper reaches of Fundy to offshore fisheries.

The history of Fundy research is an interesting one, perhaps serving as a microcosm of some of the problems confronting Canadian science. Undoubtedly stimulated by earlier sedimentological research (for example, Klein, 1970), plus the realization that tidal power might some day loom on the horizon, sedimentological and animal-sediment research underwent a boomlet from the early 1970s to the present day. In particular, the EMR-funded cooperative research between McMaster and the Atlantic Geoscience Centre has been tremendously productive. At the same time, "pure" biological research lagged drastically, with some exceptions (especially Sherman Bleakney Graham Daborn and Peter Smith and their students, at Acadia). Fundy biological research seems to have fallen between the stools of the various government institutions and universities on the east coast (its fall perhaps aided by the rigorous and dirty conditions under which such research must be carried out).

The necessary fundamental biological research is now under way, by scientists at the Marine Ecological Laboratories of the Bedford Institute, involving determination of primary productivity, sediment nutrients, and carbon budgets. Somewhat smaller programs have also been mounted by Acadia, Mount Allison, and the St. Andrews Marine Station. Unfortunately, almost five years have been lost: programs designed to measure primary productivity, carbon budgets and fish migrations were proposed to the Department of the Environment several times, beginning in 1974, and were never funded.

In fact, two types of programs are needed in the upper reaches: 1) long-term, fundamental research designed to help us understand the workings of this estuary; and 2) short-term programs designed specifically to assess the impact of tidal power development. In a recent description of the proposed environmental impact assessment procedure (Gordon and Longhurst, 1979), the suggestion is made that perhaps previous British work in the Severn Estuary could be applied to Fundy. This idea has been questioned (Risk and Buckley, in press), on the grounds that Fundy is sedimentologically very different, and there already exists a wealth of information on the sediment dynamics of the system. A computer simulation of the extent of siltation likely to be generated by a tidal power barrage is under development by David Greenberg (Atlantic Oceanographic Laboratory) and Carl Amos (Atlantic Geoscience Centre). This model, combined with the quantitative data being generated on the effect of siltation on intertidal communities (Risk, research in progress), offers a chance of providing some answers in time. Hopefully, the results of these studies will be available in time to be useful in the decision-making process because, after all, the fundamental question to be answered is, to what extent is "tidal power" already working for us?

Acknowledgements

Our work in the upper reaches would have been impossible without the field assistance provided by a number of hardworking and underpaid students: Paulette Burns, Cathy Capell, Doug Craig, Nan Ferguson, Roy Hirtle, Marika Karolyi, Jim Moffat, Brian Pratt and Verena Tunnicliffe. Research was supported by the National Research Council, Canadian Wildlife Service, and through a series of research subventions (Department of Energy, Mines and Resources) with the Atlantic Geoscience Centre, some of whose staff foresaw years ago the necessity for Fundy biological studies. Laboratory space and technical advice were provided by Dale Buckley and Kevin Robertson of the Atlantic Geoscience Centre, and by Don Gordon and Barry Hargrave of the Marine Ecology Laboratory, Bedford Institute of Oceanography. We thank the people of Hants and Colchester counties, Nova Scotia, for their interest and hospitality.

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