NATURAL AND ANTHROPOGENIC CHANGES IN THE BAY OF FUNDY – GULF OF MAINE – GEORGES BANK SYSTEM

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Abstract. The turbid, macrotidal estuaries of the Bay of Fundy system and the coastal waters of the Gulf of Maine and Georges Bank have undergone considerable change as a result of the natural processes of sea level rise, erosion, and sedimentation since the last ice age, some 14 000 years ago. In more recent times, human activities, such as marsh reclamation, bridge and causeway construction, have caused even greater modifications to these estuarine systems, influencing their productivity, and enhancing their vulnerability to further natural and human modifications.

In order to understand the effects of both man-induced and natural changes on estuarine and coastal waters, the recent history of causeways constructed in the Petitcodiac, Annopolis and Avon River systems is examined. In two instances, rock-fill barriers provided for protection of reclaimed marshlands against flooding, and for highway crossing over tidal rivers, induced formation of major mudflats on the seaward side of the causeway. Stabilisation of these flats required 10–15 yr before biological communities resembled those typically found in these estuaries. The Annapolis tidal power plant may have induced greater shoreline erosion for 25–50 km upstream. These environmental changes caused by small causeways extend over much greater distances than previously forecast, indicating underestimation of the long distance effects of modifying natural tidal flow patterns.

Proposals for much larger tidal power barrages in the upper reaches of the Fundy system stimulated extensive multidisciplinary studies of the turbid waters at the head of the Bay. These indicate that tidal power development would result in significant changes in the Gulf of Maine and Georges Bank areas, more than 400 km away. Included in these effects are an increase of 15–30% in the tidal range in the Gulf of Maine, with consequent increases in shoreline flooding and erosion, and decreases in drainage potential of low-lying coastal land. Flushing rates of estuaries are expected to increase, as is the vertical mixing pattern of shallow areas in the Gulf and on Georges Bank. The latter effect may well increase productivity of some commercially important fisheries.

Many of the predictions of the environmental impact of large-scale tidal power development are based on modelling exercises involving large numbers of scientists in many disciplines. The conclusion of this review is that human modification of estuaries can have far more extensive effects in both space and time than normally recognised. Such changes often increase the vulnerability of systems to further natural and anthropogenic hazards.

1. Introduction

Estuaries and coastal waters have played major roles in the evolution of human society in all parts of the world. Estuaries, in particular, provide for a variety of human needs: food, transportation, waste treatment, land "reclamation," sites for urban development, cooling waters for power stations, and mechanical or electrical power, for example. For centuries, man has freely modified estuaries with dykes, encroaching urbanization, construction of harbours, canals and causeways, and erection of bridges and piers.

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Within the last century our capacity to modify coastal systems has increased exponentially, and, as a consequence, many estuaries and coastal waters have suffered severe degradation (Saeijs, 1982). In more recent years knowledge of these complex ecosystems has also developed significantly, offering the hope that it will soon be possible to predict the probable consequences of estuary modification.

A common view is that small, localised developments in estuaries have only small and localised consequences. Fluid, open systems, however, derive important characteristics from interactions with neighbouring systems. Consequently, the effects of change in one system may be transmitted to others to produce effects that are extensive in both space and time. Man's increasing ability to modify natural systems, particularly through engineering works, has usually far outstripped his ability to forecast the changes in complex ecosystems. The application of integrated multidisciplinary studies, combined with computer-based modelling techniques, may offer comparable power in assessing the full consequences of human intervention. Such techniques have only recently been applied to development proposals having great scale, such as the tidal power proposals for the Bay of Fundy in Canada (e.g., Daborn, 1977; Gordon and Dadswell, 1984) and Severn Estuary in the United Kingdom (Anon, 1981). An equally urgent need is for application of similar methods to examine the cumulative effects of many small changes — e.g., coastal works for erosion control, causeway or bridge construction, harbour dredging, etc. — inflicted in piecemeal fashion on the coastal zone.

This review identifies some of the consequences of human activity in the Bay of Fundy. Our objectives are to demonstrate that human influence on estuarine systems has a long, and largely unrecognised history, and that application of modern modelling techniques offers a tool by which the hazards of human intervention can be assessed adequately.

2. Natural History of the Bay of Fundy

The Bay of Fundy is part of a larger, oceanographic unit (the FMG System) that also includes the Gulf of Maine and Georges Bank (Figure 1). The Fundy portion is a complex macrotidal estuary with two inner branches — Minas Basin and Chignecto Bay. Because of near-resonance with the 12.4 h forcing of the Atlantic tide, tidal range increases progressively in the innermost portions, and may exceed 16 m on high spring tides in Minas Basin (Garrett, 1972). Tides are semi-diurnal, and tidal currents strong ($\leqslant 5$ m sec^{-1}), particularly in narrow channels. The inner regions are characterised by large expanses of intertidal zone, 0.5 to 5 km in width, which vary from coarse sand to find mud (Amos, 1984), the latter maintaining a dynamic equilibrium with high levels of suspended sediment in overlying waters. These extensive tidal movements and associated high turbidity of the estuary are the principal environmental factors that determine the biological characteristics of the system.

The turbid, macrotidal inner regions of the Bay of Fundy system are as unique biologically as they are in physical oceanographic terms. Because of high turbidity, primary production in the water column is relatively low (Prouse *et al.*, 1984), an observation that led Huntsman (1952) to conclude that production of the inner regions was limited by tidally-derived suspended sediments. In fact, however, recent research

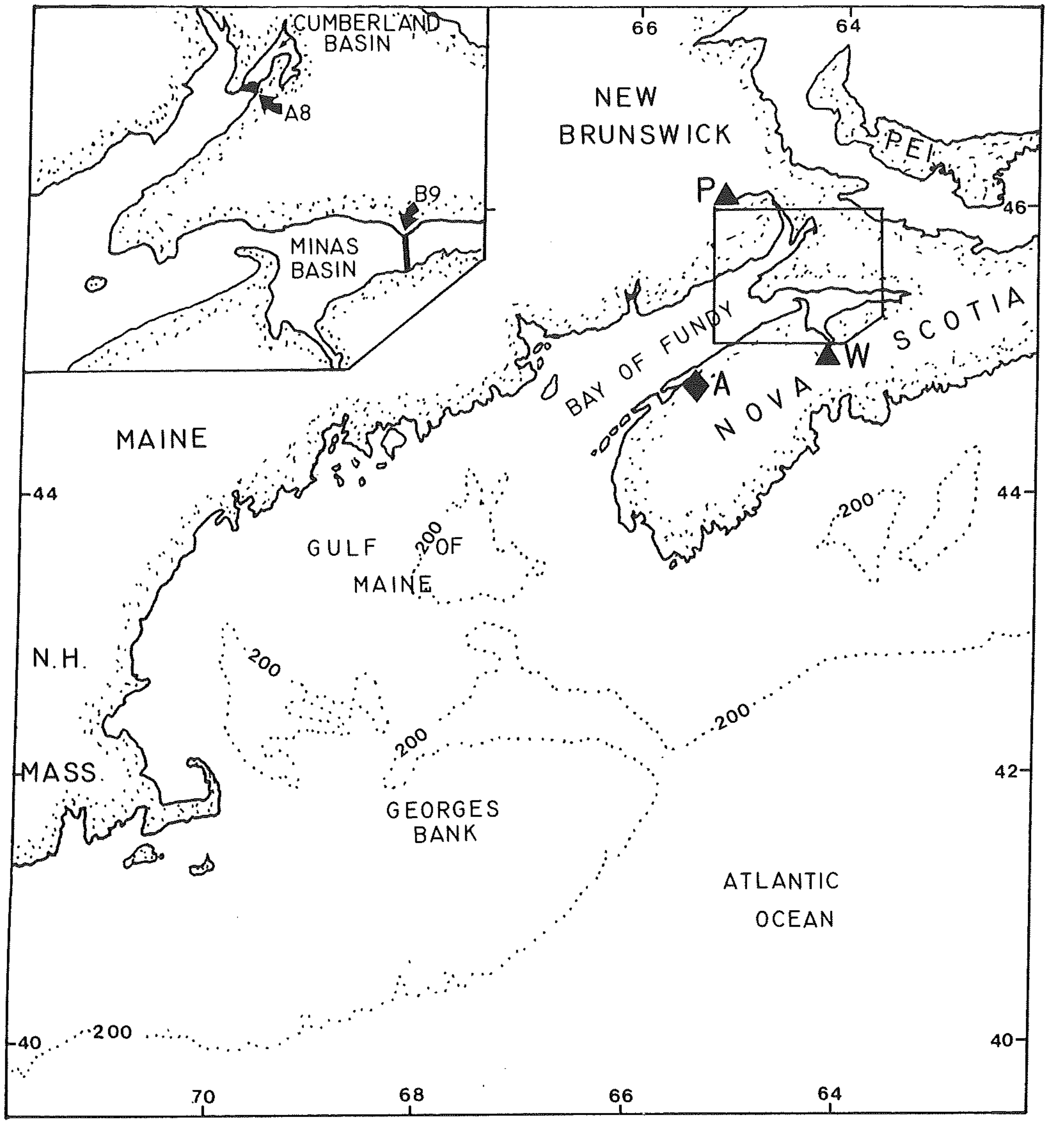

Fig. 1. Map of the Bay of Fundy — Gulf of Maine System. A8, B9 — proposed tidal power causeways, P Petitcodiac Causeway (1970), W Windsor Causeway (1969), A Annapolis Causeway (1960).

has shown that production of both zooplankton (Daborn, 1984) and benthos (Peer, 1984) may be relatively high. The basic fuel is provided partly by benthic microalgae growing on vast intertidal mudflats (Hargrave *et al.*, 1983), and partly by peripheral saltmarshes surrounding the inner basins (Prouse *et al.*, 1984). In both planktonic and benthic communities, diversity is often low, but abundance and production of organisms relatively high. These communities in turn provide the basic resources for a number of resident fish species (Dadswell *et al.*, 1984), and for major migratory poulations of fish (ibid.) and shorebirds (Hicklin and Smith, 1984), that travel to the Bay of Fundy from arctic and tropical regions (cf. Figure 3).

The macrotidal regions at the head of the Bay of Fundy are thus integrally connected with the much larger Gulf of Maine through hydrodynamic interactions, and to much of the Nearctic and Neotropical regions through biological processes. Obviously, modification of the physical properties of the system, which largely determine biological processes, may represent potential hazards that are extensive in both space and time (Daborn, 1985). Assessing the extent of the alterations presented by modern proposals for tidal power development in the inner Bay of Fundy has been the objective of a multidisciplinary research program since 1976, coordinated by the Fundy Environmental Studies Committee (Atlantic Provinces Council on the Sciences).

3. Natural Changes in the Bay of Fundy-Gulf of Maine System

Present physical characteristics of the FMG system are partly the result of major changes in sea level and geomorphological responses of the estuary during the last 12—13 millenia (Roland, 1982). With retreat of the last glaciers about 13 000 yr B.P., both sea level and land level rose, the isostatic response of the land reaching an overcompensated peak elevation approximately 5 m above present sea level about 5000 yr B.P. Since that time the land has been subsiding, while sea level has continued to rise. At times during this period, the inner Bay of Fundy varied from a lagoon, isolated from the sea by the outer banks, to an estuary with extensive tidal exchange. Amos (1977, 1978, 1984) has described postglacial changes of this systems in considerable detail, providing evidence that the tidal range has been steadily increasing. It is uncertain how much more the range will increase before changes in morphometry bring the natural period of oscillation of the Bay away from resonance with the Atlantic tide.

The physical characteristics of the system are still evolving as it responds to changes in relative sea level, and to events within the whole watershed. Present rates of sea level rise in the region are estimated at 13—21 cm century^{-1} (Scott and Greenberg, 1983), but there are concerns that these rates may be accelerating because of the global "greenhouse effect" (Titus and Wells, 1986). Shorelines of the inner bays and basins are actively eroding, and inward migration of deposited sediments resulting from tidal current flows produces continuous alterations in morphometry, and hence in the dynamic properties of the system (Amos and Joice, 1977, Amos and Asprey, 1981). These processes vary seasonally, with deposition being dominant during summer months, and greatly influenced by biological activity that affects the erodibility of deposited sediments (Daborn, Van Wagoner and Amos, 1985). Shoreline erosion is particularly active in winter because of extensive ice movements (Gordon and Desplanque, 1983). However, episodic events such as major storms, may induce more dramatic changes in erosion and deposition patterns that are unpredictable, but occur with fairly high frequency (Yeo and Risk, 1979). Major storms have varying effects depending upon the time of arrival in the area relative to stage and phase of the tide (Greenberg, 1986). The Groundhog Day storm (of February 2, 1976) produced a storm surge amplification of more than 1 m because it coincided with the high tide. Physical and biological effects were unusually extensive. The most spectacular and damaging storm recorded in the Bay of Fundy area occurred on 5 October, 1869 as a result of a gale (the "Saxby Gale") that coincided with extreme high tides associated with the nodal cycle, and a low barometric pressure. This combination yielded tidal movements estimated in excess of 21 m at the head of the Bay. The "Saxby Gale" destroyed miles of dykes, flooded thousands of acres of reclaimed marshland, and killed many cattle.

Ongoing natural changes are evident in the outer Bay of Fundy and Gulf of Maine. Sanger (1985) has provided evidence of significant changes in the Damariscotta Estuary (Maine) resulting from sea level rise during recent millenia, and it may be assumed that comparable changes are occurring in many estuaries (Larsen and Doggett, 1979). Necessarily, rising sea levels affect the extent and location of erosion and deposition events. Thus the hazard presented by storms and storm surges is likely to vary with time as estuarine morphometry continually changes.

Not all changes in tidal range are progressive. Tidal range at any locality varies according to repetitive natural cycles with periods ranging from days to years. For example, the nodal cycle has a period of approximately 18.6 yr, over which the tidal range varies by nearly 3% (Garrett, 1972). The higher tidal currents and accompanying turbulence occurring at the peak of the cycle cause associated changes in sea surface temperature (Loder and Garrett, 1978), and are correlated with changes in fish catches in the Gulf of Maine (DeWolfe and Daborn, 1985).

4. Human Impact on the Bay of Fundy

Against this background of natural change within the FMG system is a history of continuing human impact. Although many changes appear of small scale compared to the very large area of the system, cumulative effects over time and the disproportionate effects of some developments have meant that man has played a significant role in modifying the physical properties of these estuaries.

Dykeing and draining of saltmarshes to create fertile agricultural land began with the earliest European settlers, the Acadians. It has been estimated that in 1605 when the Habitation at Port Royal, Nova Scotia, was established, there were 35 700 ha of saltmarshes surrounding the Bay of Fundy (Thomas, 1977). Within a century, much of this land had been "reclaimed" from the sea and was producing large quantities of wheat, hay and other crops. Present estimates suggest that about 5—6000 ha of saltmarsh remain (Prouse *et al.*, 1984), many having reverted after dykes were broken through (as in the Saxby gale) and not repaired. Thus, about 84% of the primeval saltmarsh was converted by human activity during the last three centuries.

The significance of this conversion has only become apparent as a consequence of recent research into the productivity of the upper Bay of Fundy. Comparison of primary production rates of phytoplankton, mudflat diatoms and saltmarshes, indicate that the present day marshes produce 25 to 30% of the total production in inner regions of the Bay of Fundy (Prouse *et al.*, 1984), which supports extensive migratory and resident fish and bird populations. It is a matter of conjecture how much more productive these waters would have been when the marshes were intact and six times as extensive. Dunfield (1985), however, notes that major rivers of the system had prolific runs of anadromous fish, including salmon, gaspereau and eels. Many of these runs were eliminated by dam construction across tributary rivers in Fundy and elsewhere to provide for electricity, mechanical power or irrigation. Such structures may also reduce the input of sediment, nutrients and organic matter to the estuary.

In all likelihood, the progressive conversion of saltmarsh to dykeland, carried out in piecemeal fashion over time, has substantially reduced the productive potential of the tidal bays in favour of increasing agricultural land. In so doing, however, an element was introduced, since dykelands need to be protected against penetration by storm surges or overtopping by high river runoff. In the past three decades, protection of "reclaimed" land from spring time flooding has been the major reason for construction of causeways across tidal regions or rivers around the Bay of Fundy.

5. Causeway Construction in the Bay of Fundy

5.1. The Annapolis Causeway, Nova Scotia

In 1960 a causeway was constructed across the Annapolis Estuary at Annapolis Royal to provide a new highway crossing, and to protect 1740 ha of previously dyked marshland from tidal flooding (Figure 2). The causeway consisted of a rockfill dam, an island, and a concrete section containing sluice gates and a permanently open fishway. The dam eliminated need for continuous maintenance of miles of ancient dykes upstream, but also converted a previously homogeneous, vertically mixed estuary into a stratified, salt wedge estuary (Daborn *et al.*, 1982). On the seaward side of the dam tidal

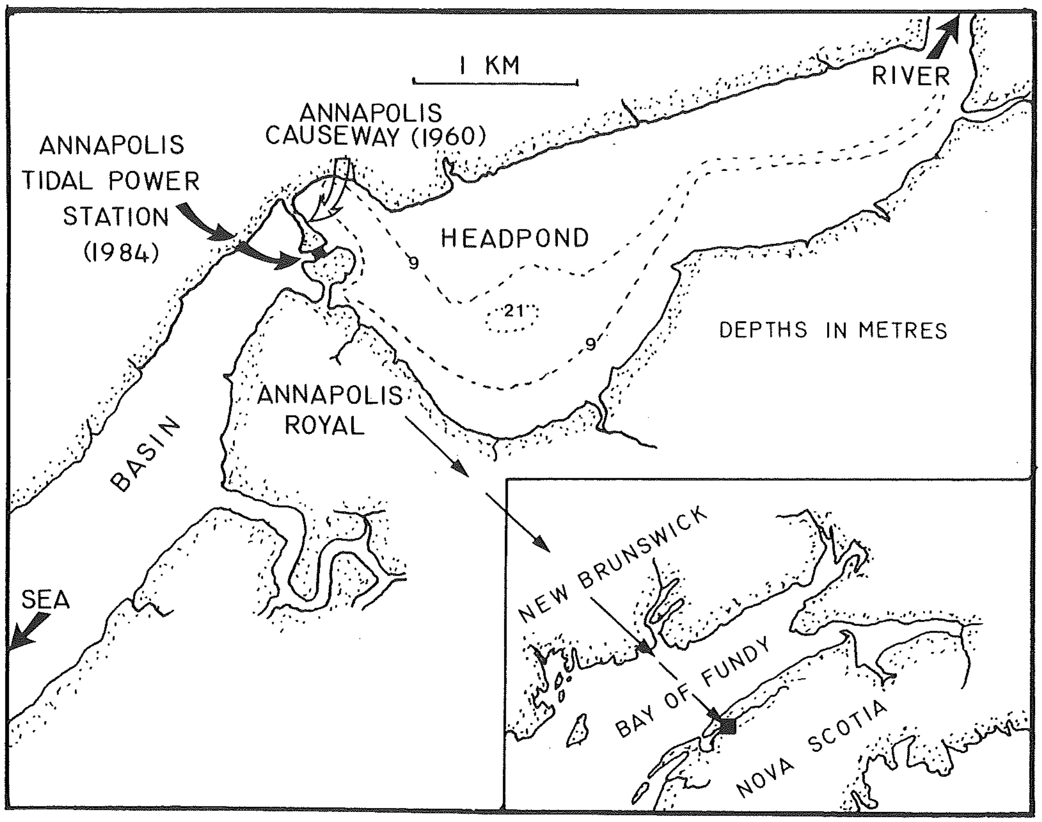

Fig. 2. Annapolis Estuary and Tidal Power Station.

range remained at 7—9 m, but on the upstream side was controlled by sluice gate operation to ± 0.5 m.

With stratification, bottom deposits over 30 km upstream, which had previously been tidal, became covered with fine silt because of the lack of tidal turbulence. Biological communities, which remained rich and abundant in the tidal regime below the dam, were impoverished upstream. Since the drainage basin includes extensive areas of bog and forest land, the river water is heavily stained with tannins and humic acids. These absorb sunlight; consequently light penetration into the stratified water column of the headpond is restricted to the upper 2—3 m, and hence all photosynthesis limited to that zone (Daborn *et al.*, 1979a; Daborn, 1986). Light penetration and photosynthesis are relatively much greater in the well-mixed tidal regime below the dam.

Direct effects on fisheries are difficult to determine because of the lack of environmental studies of the system prior to construction (Smith, 1960; Daborn *et al.*, 1979b). Salmon stocks were previously greatly reduced by construction of a hydroelectric dam on the Nictaux River upstream from Annapolis. Stocks of striped bass, shad and other river herrings may also have declined since completion of the Annapolis Causeway, although firm evidence is lacking.

From 1980—1984 the Annapolis tidal dam was further modified by construction of North America's first modern tidal power station (Figure 2). A 7 m diam. straight-flow turbine, capable of generating 18 MW in ebb-flow regime, was installed in the island portion of the tidal dam, and began full time operation in August 1984. To increase power output, mean headpond water levels were increased by approximately 1 m above the previous mean level. The turbine generates for c. 6 hours on the ebb and early flood tide at heads of 5—6 m. Filling of the headpond is achieved by sluicing through the sluice gates at high water, and may be supplemented by sluicing through the turbines when river flow is low.

The environmental consequences of this development have been far more extensive than originally predicted. As expected, increasing the flow by sluicing operations through the turbine and sluice gates has caused greater turbulence and increased vertical mixing, and promoted destratification of the headpond. The effects are seen as beneficial for development of benthic communities.

Maintenance of a much higher mean water level, however, has had serious and partly unforeseen effects on the shoreline and reclaimed marshland. Wave and ice action operating at higher levels of the shore than previously has resulted in extensive erosion up to 25 km above the causeway, threatening the existence of ancient dykes and some houses. Decreased drainage potential has caused local flooding, particularly in association with snow melt. Although there is fear of damage by salt intrusion into reclaimed marshlands, which would reduce the agricultural potential of some of the most productive farmlands in the region, evidence of damage is not yet available. Furthermore, experimental studies of fish passing through the turbine during generation indicate that mortality rates of both adult and juvenile fish are far higher than originally predicted (Hogans and Melvin, 1985; Stokesbury, 1986).

In general, despite a relatively complex review of anticipated environmental effects of the development (Daborn *et al.*, 1984), the construction and operation of the Annapolis Tidal Power Station has produced more far-reaching effects in space and time than expected. It has significantly altered the natural hazards commonly affecting shorelines (e.g., by wave and ice erosion), and threatens to diminish both agricultural and fishing production, with serious implications for local communities. Unfortunately, the special estuarine characteristics of the Annapolis system distinguish it from other sites where tidal power development is contemplated. Consequently, the Annapolis project is not a very satisfactory paradigm for proposed stations in Cumberland Basin and Minas Basin (see below).

5.2. The Petitcodiac Causeway, New Brunswick

From 1968—70, a 1050 m long causeway, including five sluice gates and a fishway, was constructed across the Petitcodiac River near Moncton, N.B. (Figure 1). As with the Annapolis Causeway, the objectives were to prevent flooding of reclaimed marshlands and provide a highway crossing (Bray *et al.*, 1982). Location of the causeway was approximately 21 km below the previous head of tide, and about 34 km from the month of the river. Tidal elevations at Moncton ranged from 4.5—8.0 m with a mean of 6.1 m. A conspicuous tidal bore of 10—20 cm was evident on spring tides. Tidal resuspension of fine clay and silt-size particles from the extensive mudflats maintained a very high turbidity in the water column, with suspended sediment loads of 10—25 g L^{-1} near Monction. Such extremely high turbidity is characteristic of most river systems at the head of the Bay of Fundy, and distinguishes these from the relatively low turbidity of outer estuaries like the Annapolis.

Within two years of closure of the causeway, a massive mudflat some 20 km in length had formed on the seaward side of the causeway. Rates of siltation were rapid, the new mudflat rising upward at 1.5—2 m per year in places. By 1981 more than 10×10^6 m^3 of mud had accumulated in the uppermost 54.7 km alone (Bray *et al.*, 1982), and the reduction in estuarine cross-sectional area was about 20%. In addition, the permanently open 2.5 m wide fishway permits a mean net accumulation of 380 m^3 ($\simeq$ 430 tonnes) of sediment upstream of the causeway on each tide. Virtually all the sediment entering the reservoir through the fishway is trapped upstream. As with the Annapolis case, increased water levels are associated with significant wave action, producing dynamically unstable beaches where the erodible surface is of fine particles such as silt and clay.

5.3. The Windsor Causeway, Nova Scotia

A similar sequence of events accompanied construction of a causeway across the Avon River near Windsor, N.S. (Figure 2). A 900 m impermeable rock-filled dyke with a sluice control structure was completed in 1969. Within six years a mudflat 750 × 600 m in dimension had formed on the seaward side, representing the accumulation of about 1.8×10^6 m^3 of sediment (Amos, 1977a, b; Amos and Joice, 1977). Rates of growth still exceeded 15 cm $month^{-1}$ in some regions, and now, after 16 yr of continued growth downstream, continued shallowing of the estuary is considered to be a serious threat to shipping activities at Hantsport, the last remaining major port in the upper Bay of Fundy, some 8 km downstream. Biological investigations have shown that the new mudflat is at first too fluid for colonisation by the normal benthic organisms that make Fundy intertidal habitats so productive (Risk *et al.*, 1977). After some 15 yr natural consolidation processes have stabilised surface sediments, and created new and productive feeding grounds for migratory shorebirds.

These three examples demonstrate the surprising extent of environmental effects resulting from causeway construction within areas of tidal flow. Morphological changes to the estuary occur over many years, and involve the complete estuarine system, not just the immediate region of the construction. Although ex post facto analysis of these events has contributed much to our recognition of essential processes and improved our ability to predict the consequences of estuarine modification, the site-specific nature of changes makes extrapolation from small existing barriers to proposed large scale ones extremely difficult.

6. Proposed Tidal Power Developments

The earliest proposal for harnessing tidal power in the Bay of Fundy was made in 1910, and since that time there has been a succession of proposals (Baker, 1982). Following an examination of 23 possible sites, two locations were finally selected that had favourable economic and sociopolitical features: the Minas Basin-Cobequid Bay site (B9) and Cumberland Basin site (A8) (Figure 1). The most recent designs require an 8 km concrete caisson barrage at B9, and a 2.6 km barrage at A8 (Dadswell *et al.*, 1986). Energy output would be 5338 MW at B9 and 1428 MW at A8, with estimated construction costs of $7.0 billion and $2.6 billion, respectively.

The predicted environmental effects of these constructions are manifold and widespread in both space and time. As a result of removing tidal energy and reducing the volume of water passing the barrage site, the tidal regime on each side will be changed. A mathematical model prepared by Greenberg (1977) predicts that tidal range will decrease just seaward of the barrage, but increase in the outer Bay of Fundy and Gulf of Maine by as much as 15% as a result of the B9 development. Behind the dam, tidal range will be reduced to 5—6 m, and mean water level will be higher. Some stratification should occur in the headpond, and reduced tidal energy would be expected to decrease water column turbidity, but increase sedimentation behind the dam (Amos, 1984). Most sedimentation will probably occur in peripheral regions of the headpond, because turbulence associated with generation and sluicing should maintain sediments in suspension in central areas. Although it is not expected that the working volume of the headpond will be significantly decreased, the ecological effects of sedimentation will be substantial. As with the Petitcodiac and Windsor cases, sediment accumulation will continue until a new equilibrium is reached, which is determined by the amount of energy to be dissipated by friction. Biological colonisation of the new deposits is likely to be slow, requiring one or more decades before biological communities resemble those typical of intertidal or subtidal deposits in the Fundy system. Ultimately, new saltmarshes may develop that, together with increased phytoplankton production, would lead to an overall increase in productivity of the region (Daborn, 1985). There would, however, be significant changes in the structure of the biological community in both the water column (Daborn *et al.*, 1984) and the benthos (Daborn, 1986).

Major impacts are expected on the fisheries of the region. Both proposed barrages traverse the migration routes of important anadromous fish that spawn in local rivers. These species include salmon, shad, striped bass, river herrings, smelt and others, all of which are important regional fisheries (Dadswell *et al.*, 1984, 1986). In addition, other coastal and riverine populations of fish visit the upper Bay of Fundy system for feeding

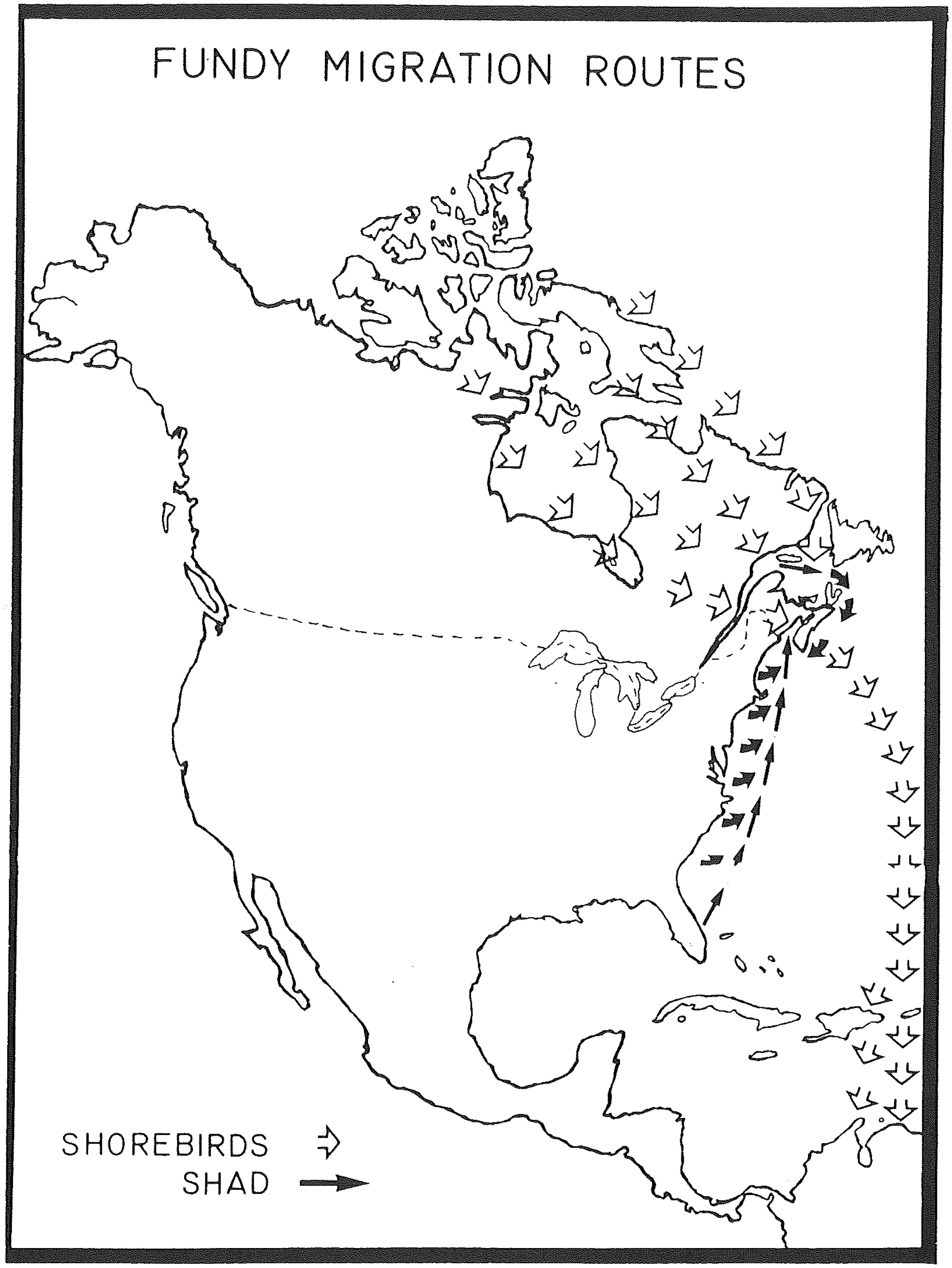

Fig. 3. Migration routes of American shad (solid arrows) and shorebirds (open arrows) to the Bay of Fundy.

during the summer months before returning to home spawning areas (Figure 3). Experience with the Annapolis turbine suggests that early predictions of 10% mortality to large fish (> 50 cm) may be underestimated (Hogans and Melvin, 1985), and that mortality of juvenile and smaller fish will also be significant (Stokesbury, 1986). Turbine mortality may affect populations over the whole Atlantic coast of North America.

The impact on migratory shorebird populations is more difficult to assess. Reduction of the intertidal area behind the barrage, and changes in mud- and sand-flat distribution to seaward could markedly reduce the available foraging area. Although at present there appears to be no food shortage, behavioural interactions may interfere with successful foraging by birds.

The long range impact of tidal power developments thus is reflected in both physical and biological processes. Increased tidal range in the Gulf of Maine is expected to increase the hazards to human communities in the region through flooding, storm surge damage to coastal structures, and decreased water quality in wells (Larsen, 1981, Larsen and Topinka, 1984). Many existing sea walls, piers and jetties may need to be modified to compensate for changed high water levels. Of course, the steady natural rise in sea level will necessitate similar changes, although over a longer time period (Titus and Wells, 1986). These negative impacts may, however, be counterbalanced by positive changes in fisheries productivity associated with greater mixing in shallow regions of the Gulf of Maine (Campbell and Wroblewski, 1986; DeWolfe and Daborn, 1986).

7. Predicting the Impact of Tidal Power

The complexity of estuaries and coastal waters remains a major barrier to decision-making in relation to coastal zone management. Each estuary exhibits a unique combination of features, so that the effects of human intervention tend to be site-specific, with limited potential for extrapolation from one site to another (Daborn, 1985). Nevertheless, physical processes are moderately well known as a result of decades of work by scientists and engineers (Komar, 1983), and the development of sophisticated hydrodynamic computer models has permitted the consequences of human modification of coastal zones and estuaries to be explored over much greater time and space scales than previously possible (Bruun, 1985). Concomitantly, there has been a much enhanced recognition of the extent to which human activities impact upon the coastal marine environment, often to the detriment of human safety, protection and preservation of property, and conservation of important marine resources.

Exploration of the potential effects of tidal power development has also been based upon hydrodynamic and ecological simulation modelling in regard to the Bay of Fundy (Greenberg, 1977, 1985; Gordon *et al.*, 1986), the Gulf of Maine (Campbell and Wroblewski, 1986) and to the Severn Estuary (Radford, 1981). Such models are often based upon perceptions rather than empirical observations, and have in common a paucity of hard data. Although the models satisfactorally describe existing conditions they have not been adequately verified, and predictions of the effects of human modification based upon them remain largely speculative and tentative but nevertheless quite valuable. It may be that only construction of a large tidal power development, such as that proposed for the Minas Basin or Severn Estuary, will permit us to appreciate the full extent of the hazards to human welfare represented by these proposals. Clearly such a process is accompanied by considerable risk.

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