Chapter 25

POTENTIAL IMPACTS OF HYDRO AND TIDAL POWER DEVELOPMENTS ON THE ECOLOGY OF BAYS AND ESTUARIES

Graham R. Daborn

Acadia Centre for Estuarine Research

and

Department of Biology
Acadia University
Wolfville, Nova Scotia BOP 1XO

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INTRODUCTION

As shown in the previous chapter, the downstream impact of inland hydro developments has been the subject of much investigation in recent decades. Rarely, however, has consideration been given to the potential effects such developments have on estuaries and coastal bays near the mouth of the river, perhaps because it has usually been assumed that these receiving waters were too remote from the site of the development. The events following closure of the Aswan Dam in 1964 clearly demonstrated that downstream effects may not only be extensive in space, but have profound effects on the complex and productive ecosystems of the coastal zone (1).

The characteristic features of estuaries depend to a large extent upon the interaction between river runoff patterns and tidal or wind-induced movements of the sea (2). Consequently, major hydro developments that influence the seasonality and/or volume of freshwater input to the coastal zone may have important effects that ramify throughout the coastal ecosystem. Furthermore, even small, localised hydro developments on tributary rivers may have observable impacts upon estuaries because their effects are often cumulative (3): several small projects may have a total effect similar to a single large development.

Failure to recognise the potential long distance effects of hydro developments is only part of the problem. Another important impediment to adequate prediction of the impacts of man-made changes on estuaries and coastal waters is the very complexity of these systems. Each system is unique. Developing sufficient understanding of the properties of the system to permit adequate modelling or prediction of impacts requires a broad range of basic information on hydrology, biogeochemical cycles, biophysical and interspecific interactions, etc. Often these have changed considerably over time for natural or anthropogenic reasons. Nonetheless, concerted, multidisciplinary research efforts may yield enough knowledge of a system within a few years to allow such predictions to be made with some confidence. This has been demonstrated, for example, by major projects in the Dutch Delta (4), and in relation to tidal power proposals in the Severn Estuary (5) and the Bay of Fundy (6).

In many respects, tidal power proposals differ from those of more traditional hydro power developments. Located in the zone of tidal influence, the power to be captured comes largely from the ebb and flow of coastal waters, rather than from retention of large volumes of river water in a reservoir. Turbines must be able to operate efficiently under relatively low heads (<5 m). The time of generation is usually set by the tidal flux, and thus changes from day to day by about 50 minutes, in contrast to river hydro, where generation may be matched to regional peak demand. In other respects, however, the two types of development are more similar. Both modify the timing of natural flow patterns, with wide-ranging effects on sedimentation and erosion processes, on productivity, and on the fate and distribution of benthic animals. Both may intersect the migratory routes of fish, although the estuarine location of a tidal power dam makes this feature more prevalent.

In this chapter I shall use recent experiences gained in relation to large scale tidal power proposals to exemplify some of the major influences that tidal and hydro power developments may have on coastal and estuarine waters.

TIDAL POWER PROPOSALS

Tidal power is an old technology: tidal mills were in operation in 11th century Europe and probably much earlier, and some of these continued to operate until the mid-19th century (7,8). Modern proposals, however, are typically of much greater scale, and involve production of electrical rather than mechanical energy. At the present time, modern tidal power plants of varying size operate in four countries, but there are numerous other sites around the world where developments have been or are being considered (Table 1).

All existing plants and those that have been seriously considered, are of the same conventional design (Fig. 1). This involves a concrete or rockfill dam, containing turbines and sluice gates, that extends completely across an estuary with relatively large tidal range (>5 M). The dam is used to retain water in a large upstream headpond. This is filled through sluice gates on the rising tide, until sufficient head develops between the headpond and falling sea levels to operate the turbine efficiently. At this point the turbine gates are opened and generation proceeds for about 6 1/2 hours before rising sea levels once again eliminate the head of water. In most designs less than half of the water in the headpond can be passed during a generation cycle. Consequently, the design leads to retention of a large volume of sea water above the dam (Fig. 1), and a consequent conversion of previously intertidal habitats to subtidal ones. Alternative designs involving vertical axis turbines have been suggested, but these at present are only in early stages of development.

In sites with very large tidal range, such as the Bay of Fundy (<16 m), Severn Estuary (<12 m), and La Rance Estuary (<13 m), it is possible to generate power both on rising and falling tides. At La Rance, variable-pitch bulb turbines are used in this "double effect" mode, but economic considerations generally favour "single effect" ebb tide generation. This is partly because the cost of unidirectional turbines is much less than bi-directional ones, and because the total power output may be almost the same since the headpond can be raised to higher levels by sluicing if only ebb generation is considered. Construction costs vary considerably from site to site, and power yielded depends both upon the tidal range and the volume of water passing the point of construction. Consequently, cost-benefit analyses produce extremely varied results for different sites. With the conventional design, the complete dam must be constructed before power can be generated, resulting in a heavy 'front-end' financial loading such as occurs with other hydro developments.

In both the Bay of Fundy (Fig. 2) and the Severn Estuary (Fig. 3), several sites and plans have been considered for their potential suitability for tidal power generation, but the number has generally been reduced to a few that exhibit the best cost-benefit relationships. Since each location is unique in the specific combination of oceanographic and biological properties, environmental effects vary considerably from site to site.

In the Bay of Fundy, proposals for tidal power development were first made in 1910, again in 1919, and in the 1950s with reference to Passamaquoddy and Cobscook Bays in the outer Bay of Fundy region (8). Physical oceanographic and fisheries investigations were stimulated by these proposals, leading to the first systematic ecological studies of these macrotidal estuaries. Eventually the projects were always abandoned for economic reasons (once after some initial construction had begun), although environmental concerns were raised in each case. Interest in new proposals for tidal power developments in the upper Bay of Fundy (notably Minas Basin, Cumberland Basin and Shepody Bay - Fig. 2) was reinforced by the rapid escalation of oil prices in the 1970s. In order to assess the probable environmental consequences, a multidisciplinary research programme was established involving government and university scientists with a broad mandate to examine all aspects of the Bay of Fundy. This programme was coordinated by the Fundy Environmental Studies Committee (Atlantic Provinces Council on the Sciences). A similar multidisciplinary team was created for the Pre-feasibility Study of the Severn Barrage (5).

ENVIRONMENTAL EFFECTS OF TIDAL POWER

Physical Effects

Construction of large tidal barriers involve major changes to patterns of water flow throughout the estuary and the coastal waters with which it is connected. Macrotidal estuaries such as Fundy and the Severn are tidally dominated systems: the water column tends to be completely mixed from top to bottom, and to carry high levels of suspended sediment that are maintained in dynamic equilibrium with intertidal and subtidal deposits. Construction of a barrier with sluice and turbine units will necessarily change patterns of water flow, and produce significant decreases in turbulent mixing over much of the new headpond. Where freshwater inputs are large, stratification of the water column should occur in peripheral regions of the headpond, although strong currents generated during sluicing may maintain the mixing and turbidity in central portions. Where stratification occurs, sediments will tend to settle and accumulate, allowing greater light penetration, but converting many firm or sandy substrates to muddy ones. Experience with causeways built across small estuaries in the Fundy system has shown that very large accumulations of fine silts can occur at rates too rapid to permit dewatering. The resulting wet sediments are treacherous and biologically unproductive for many years after the accumulation has begun (3,11).

Seaward of the barrage, there will be local changes in the distribution and size of mudflats and sandflats as the pattern and strength of tidal currents will be modified. These are quantitatively difficult to predict without knowledge of the siting of turbine and sluice units.

The most far-reaching physical effects of barrage construction, however, are caused by changes in the resonant frequency of the estuary. Macrotidal estuaries derive their characteristic high tides in part from the near-coincidence of their natural oscillating period (a function of morphometry) with the forcing period of the ocean tides. The natural period of the Bay of Fundy - Gulf of Maine system is about 13 h: shortening the Bay by building a tidal barrage in the headwater region will bring this natural period even closer to the 12.4 h forcing period of the Atlantic tide. Present mathematical models predict that the Minas Basin barrage (B9) will cause a 10-15% increase (20-30 cm) in tidal range in the Gulf of Maine because of enhancement of resonance (12). In effect, the Bay - Gulf system will be "tuned" more closely to the natural tidal frequency. Increases in tidal range will cause greater vertical mixing in shallow areas of the Gulf. This, in turn, will decrease sea surface temperature because of the increased upwelling of cool deeper water, and possibly increase the incidence and extent of coastal fog. It should also increase the recycling of important nutrients, particularly nitrogen and phosphorus, with obvious implications for biological productivity.

Interestingly, precisely the opposite effect is predicted for the Severn barrage (13). The natural period of the Severn Estuary - Bristol Channel system is about 11 h--thus, shortening the system with a tidal barrier should, if anything, decrease the tidal range throughout because the system will be moved further away from resonance.

Biological Effects

Because macrotidal estuaries are physically dominated systems, all changes in physical properties--currents, sedimentation patterns, light penetration, etc.--are expected to have profound and far-reaching biological effects. As with most natural ecosystems, knowledge of biological processes is generally much less satisfactory than that of physical ones, and predictions of biological effects are consequently more generalised and less precise.

Despite the apparently harsh environmental conditions of strong tidal currents, high turbidity, and extreme ice action in winter, the Inner Bay of Fundy harbours a biological community of surprising variety and productivity. The major source of primary production fuelling the system appears to be the peripheral saltmarshes, particularly the lower _Spartina alterniflora_ zone (14). This is supplemented by benthic diatom production on intertidal mudflats. Phytoplankton production is low except in outer regions where turbidity is less. The saltmarshes yield large quantities of leaf material that decompose on the mudflats or in the water column, and are broken up by epibenthic and benthic macroinvertebrates such as mysids, crangonid shrimps and amphipods. The fine fragments are consumed by small particulate feeders such as copepods and larvae of benthic molluscs and polychaetes (15), which in turn provide primary food resources for some resident and migratory fish. Diatom production on the mudflats is consumed by benthic deposit feeders, particularly the amphipod _Corophium volutator_, the clam _Macoma balthica_ and some polychaetes. _Corophium_ constitutes the major prey of some migratory shorebirds and many fish. Both of these food chains (cf. Fig. 4) are relatively short, so that a great deal of the intertidal biological production is quickly conveyed to the birds and fish foraging in the estuary.

With construction of a tidal power barrage, both sources of primary production will be reduced in the headpond region: the area of intertidal zone will be almost halved, with a corresponding reduction in benthic diatom production, and, unless remedial measures are taken, existing saltmarshes will be overtaken by terrestrial vegetation because the new high water level behind the dam will be lower. Although the latter effect will be transient, saltmarsh development down the shoreline to a new equilibrium position will be a slow process, and therefore the major contribution of the marsh will be reduced for at least a decade after completion of the dam.

Higher production by phytoplankton in the clearer, nutrient-rich waters of the headpond will compensate to some extent for the decline in saltmarsh and benthic diatom production. The shift toward greater pelagic primary production should favour food chains involving planktivorous organisms (e.g., herring, menhaden, cnidarians) and benthic suspension feeders such as mussels (16). Similar predictions have been made on the basis of an ecosystem simulation model (GEMBASE) for the Severn Estuary tidal power proposal (17).

Very different concerns apply to the seaward side of the barrage. Because of changed current patterns, the mud- and sandflats will become redistributed, requiring some time (e.g., 10-20 years) before they have stabilised and harbour the benthic communities typical elsewhere in the system. There is no anticipation yet that the relative proportion of muddy and sandy environments will change: hence no long-term change in benthic productivity due to sediment type is expected.

This conclusion is of great importance. During the last few years it has become evident that the headwaters of the Fundy system are of immense importance for migratory birds and fish. From mid-July through September the mudflats of the upper Bay are visited by vast numbers of small shorebirds, particularly sandpipers and plovers, that are on their fall migration from arctic breeding grounds to wintering grounds in the Caribbean or South America. It has been estimated that more than half of all the birds nesting in the eastern and central Canadian arctic visit the Bay of Fundy on their way south. While there they forage extensively on the mudflats, each bird often consuming hundreds or thousands of benthic animals per day. Studies have shown that during an average stay of 2-3 weeks, a semipalmated sandpiper may double its weight (from 16 to 32 g), by consuming hundreds of thousands of *Corophium* (18). The fat accumulation is essential for a subsequent non-stop oversea migration of more than 4,000 km to the wintering grounds. Upon arrival, the shorebirds weigh once more what they weighed on first arrival at the upper end of the Bay. Clearly, the sojourn in the upper Bay is of critical importance.

Construction of a tidal power barrage, and the consequent reduction of intertidal zone and redistribution of mudflats, may well have significant effects on these transient consumers.

Although estimates of abundance and feeding rate of shorebirds suggest that only a small fraction (<5%) of the available benthic secondary production is currently consumed, the long time for adjustment of sediments, and deleterious effects of overcrowding on remaining feeding grounds (19), may well be damaging to migratory bird populations.

Furthermore, the currently abundant benthic resources are also utilised extensively by fish. During summer months, the waters of the upper Bay system are the feeding grounds for more than 50 species of fish. Some are year-round residents, but most species are part of stocks that move in and out of the Bay from the continental shelf. Included in this group are such commercially important species as herring, cod, halibut, haddock, hake and pollock. Many anadromous fish that spawn in rivers tributary to the upper Bay also feed there--including salmon, striped bass and river herrings. Finally, there is an important group of fish that migrate over large stretches of the Atlantic coast into the upper Bay, where, like the birds, they find abundant and important food resources (20). The best known example is the American shad, a commercially import species in the U.S., which spawns in east coast rivers from southern Florida to the Gulf of St. Lawrence. Recent research suggests that most, if not all, shad visit the upper Bay of Fundy at least once during the 3-4 years spent at sea before returning to home rivers to spawn (21). Other examples include striped bass, alewife, and blueback herring.

Direct impact on larger fish is to be expected where natural movements will bring them through the location of a tidal power barrage. During spawning runs, fish may be able to reach home rivers by moving through the sluice gates on the rising tide, but when travelling to sea, the only or most obvious open passage will probably be the turbines during generation. For feeding migrants such as the shad, repeated movements into and out of the headpond may entail successive passages through the turbines (20). Experiments with the tidal power station at Annapolis Royal have shown that mortalities of large fish such as the 50-cm-long shad may be high: c. 20% on each pass (21). Even juvenile fish suffer unexpectedly high mortalities (22).

Although the problems posed by migratory animals have generated much of the interest and controversy that surrounds Fundy tidal power proposals, the most far-reaching consequences may well be associated with changes in the tidal amplitude in the Gulf of Maine, 300-800 km away. As indicated before, the Minas Basin barrage is expected to increase tidal range in the Gulf by about 10-15% of the present range, although the magnitude varies somewhat according to the design and manner of operation of the barrage (23). Such a change could result in an increase of 15-33% in tidal mixing energy (24). Usually, mixing increases pelagic productivity because it recirculates essential nutrients from deeper water to the surface where it may stimulate phytoplankton growth. This enhancement is expected to result in increased fish production in certain portions of the Gulf (25). An independent set of evidence for this has been found in correlations between fish catches in the Gulf and the natural 18.6 year nodal cycle of the tides: landings of some important commercial stocks, such as cod, halibut and haddock, peak following the years of maximum tidal range (26). The effect is detectable even though the modulation of the tide is only about 3-4%--about the increase that would be caused by the proposed Cumberland Basin tidal power development, but considerably less than that for the Minas Basin one. Enhanced fish production in one of North America's most important fishing grounds might be an environmental benefit that partly compensates for other increases in fog, flooding, drainage problems or fish mortality associated with passage through turbines.

Large scale tidal power development thus represents a very mixed bag of environmental effects. What such proposals have shown, however, is the extent to which the river and estuary may be connected with a much larger coastal system. It clearly necessitates a very large scale holistic approach to evaluation of the potential for tidal power.

COMMON FEATURES OF TIDAL AND RIVER HYDRO DEVELOPMENTS

In spite of the highly site-specific nature of tidal and hydro developments, there are some features in common. Both change important characteristics of outflow from the river. Both may influence erosional processes above and below the point of construction, with related influences on sediment accumulation. As far as receiving systems are concerned, changed temporal patterns of water flow may have significant impacts on mixing characteristics of estuaries and coastal waters, with far-reaching biological consequences.

Large scale hydro dams often modify the annual pattern of outflow, particularly where patterns of precipitation are strongly seasonal. The downstream effects of such change on riverine fauna is well known; the impact of such change on estuaries and enclosed seas, however, has not often been considered (27). A dramatic illustration of this impact has been provided by construction of the Aswan High Dam. Prior to closure in 1964, the majority of annual outflow (c. 3×10^9 m^3) from the Nile occurred in September and October, delivering large quantities of phosphates, silicates and silt to the eastern Mediterranean, and stimulating spectacular blooms of phytoplankton (28). High plankton densities supported major fisheries for sardines (*Sardinella* spp.) that totalled 18,000 t. in 1962. Following closure, the seasonal flood effect was largely eliminated: phytoplankton concentrations in October dropped to 10% of previous values, and the sardine fishery collapsed. It has not recovered.

Large scale modifications of seasonal flow patterns from hydro developments that influence bays and coastal waters have occurred in many other river systems. In North America, obvious examples include the St. Lawrence (29), San Francisco Bay - San Joaquin - Sacramento system (30, 31) the Santee - Cooper (32), and the Colorado - Gulf of California system (33). Man-made reservoirs act as sediment traps, reducing the important outflow of silt and nutrients into the estuary. While this may reduce the problems of eutrophication experienced in other estuaries receiving excessive nutrient input, and diminish to some extent the deleterious input of heavy metals and pesticides, it also may reduce important nutrient supplies that fuel more nutrients--limited coastal ecosystems.

Changing the seasonal flow pattern from the river can have far reaching effects, not just in the river and estuary. It has been suggested that progressive development of several small reservoirs and one giant one (Manic 5 with a storage capacity of 140 km^3) in the St. Lawrence watershed is having profound effects on the entire ecosystem of North America from the Gulf of St. Lawrence to Cape Cod (34). Outflow from the river influences the degree of vertical mixing in the estuary. This has been correlated with changes in the production of haddock, halibut and lobster stocks in the Gulf of St. Lawrence which show increased catches 8, 10 and 9 years (respectively) after years of peak outflow (35). These lag times correspond approximately to the time for development to catchable size in each species.

As with tidal power developments, fluctuations in the amount of river outflow relative to the tidal prism may well produce profound biological changes within the system--influencing the extent of benthic-pelagic coupling, for example (2), or the relative importance of pelagic and benthic food chains. Such modifications, effective over large areas of the coastal zone, might well have unacceptably high costs in terms of decreased fishery productivity. When these are added to turbine-induced mortalities of anadromous or estuarine fish populations, the economic value of large scale hydro or tidal power developments may be viewed very differently.

In the final analysis, however, the justification for interference with natural estuarine and coastal ecosystems by power developments must be determined by recognition of all consequences--environmental, social and economic. In this context it is also essential to recognise the costs of not proceeding with the development. If, for example, the alternative to tidal power development in Eastern Canada is increased use of Nova Scotia coal by thermal generation, the 1-5% sulphur content of that coal will create much more negative environmental effects in the atmosphere without the compensatory advantages that might be seen in the tidal power effect on the Gulf of Maine fishery (36). Prudent development decisions demand a perspective that is both comprehensive and global.

Table 1. Existing and Proposed Tidal Power Plants

a) Existing plants

Country	Site	Completion Date	Output (MW)
France	La Rance	1966	240
U.S.S.R.	Kislaya Bay	1969	0.4
People's Republic of China	>120	Since 1959	7900 (total)
Canada	Annapolis Royal	1984	20

b) Proposed developments

Country	Site
Argentina	San Jose Gulf San Julian Gulf Deseedo Estuary Gallegos Estuary Santa Cruz Estuary
Australia	Secure Bay Walcott Inlet St. Georges Basin George Water
Canada	Minas Basin Cumberland Basin Shepody Bay Ungava Bay
France	Chansey Is. Mount St. Michael
India	Gulf of Kutch Ganges R. Gulf of Cambay
Korea	Seoul R. Inchon Bay Garolim Bay
United Kingdom	Severn R. Solway Firth Strangford Lough Mersey Estuary
U.S.A.	Cobscook Bay, Maine Friar Roads, Maine Half Moon Cove, Maine Cook Inlet, Alaska
U.S.S.R.	White Sea Penzuina Gizhiga

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FIGURE CAPTIONS

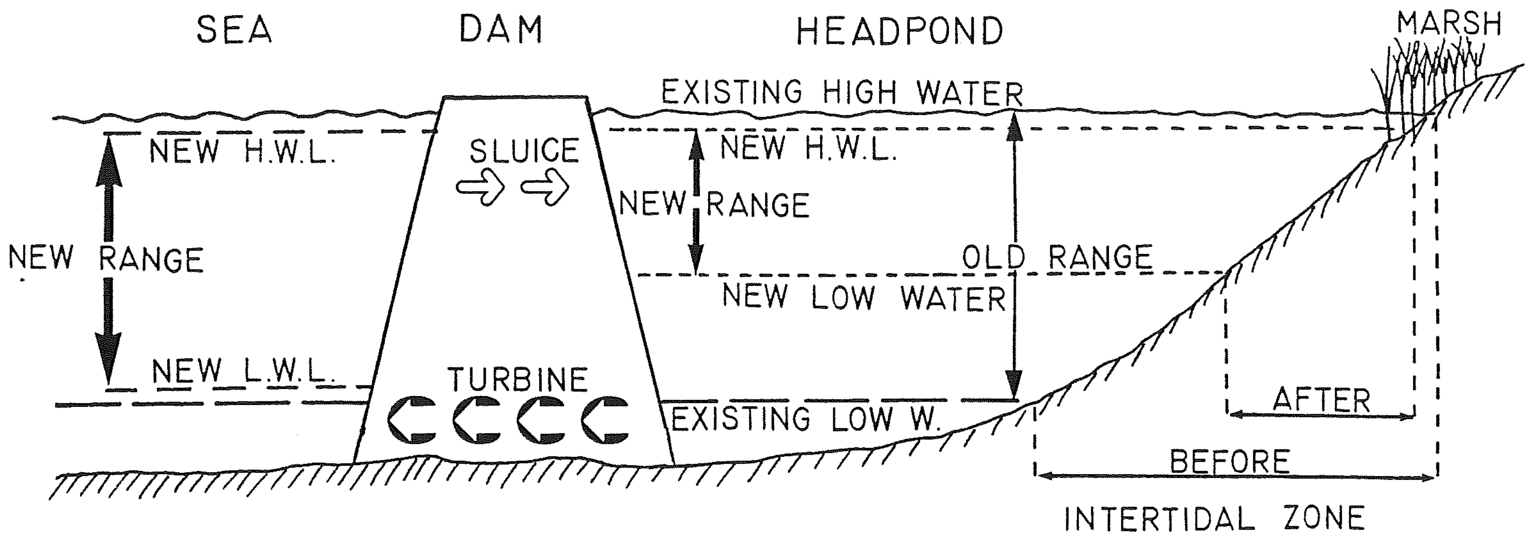
Fig. 1 Conventional tidal power development.
HWL - high water level
LWL - low water level

Fig. 2 Proposed tidal power developments in the Bay of Fundy. (N.B. Some smaller dam sites omitted for the sake of clarity.)

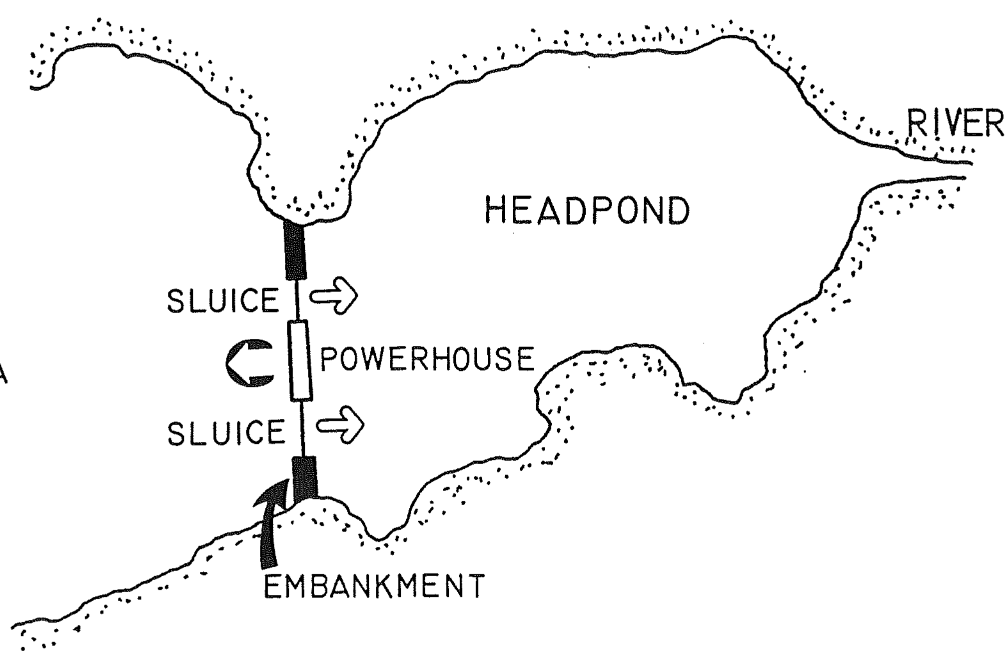
Fig. 3 Proposed tidal power developments in the Severn Estuary. T - turbines, S - sluices, L - ship locks. Solid bars represent rockfill/concrete embankments.

Fig. 4 Simplified food webs of the upper Bay of Fundy.
A - "pelagic" food web based largely on saltmarsh detritus and functioning in the water column;
B - "benthic" food web based largely on benthic diatom production when intertidal zone is exposed;
E - export of production from the upper Bay;
LWL, HWL - low water level, high water level.

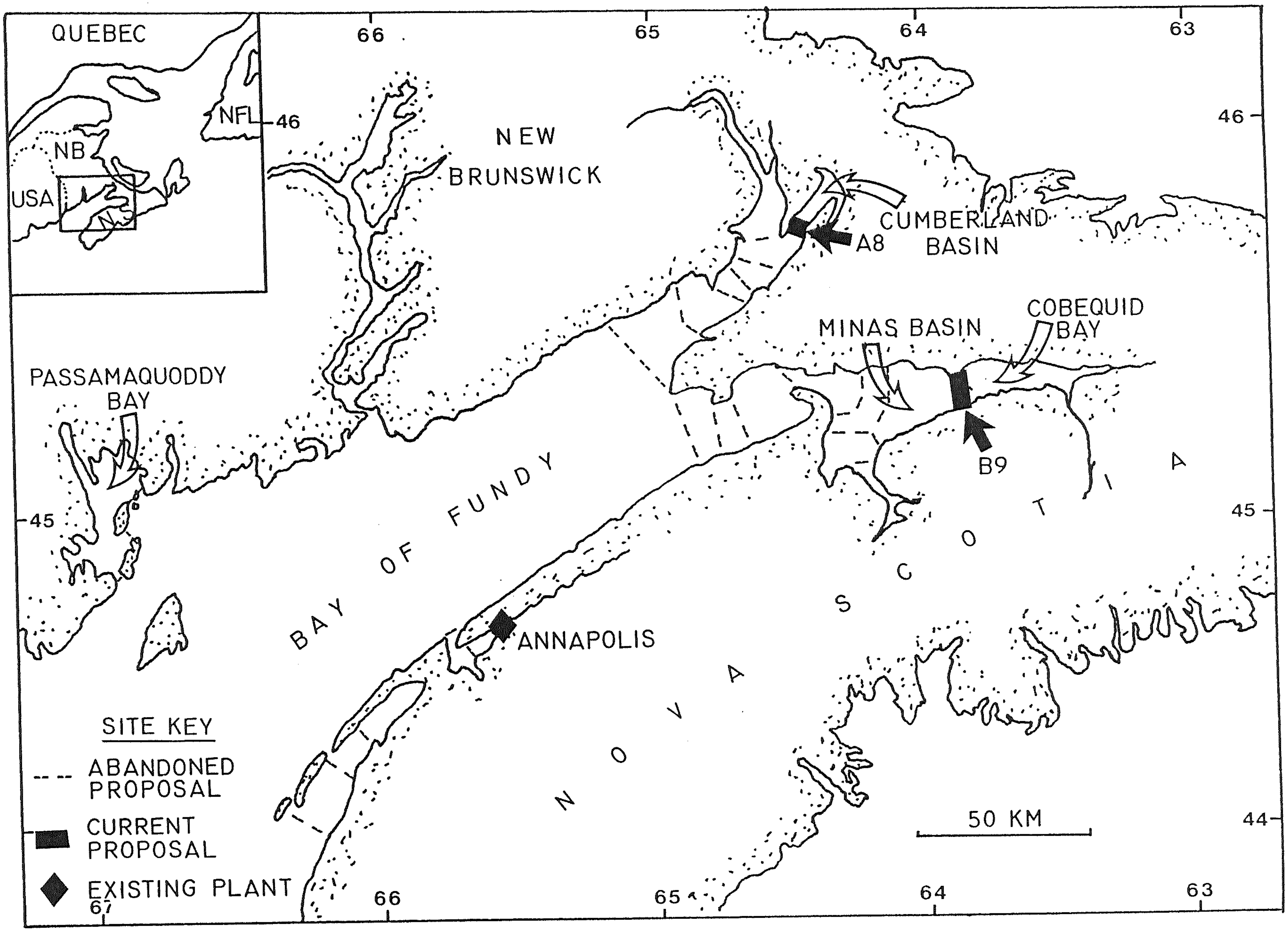
A) SECTION



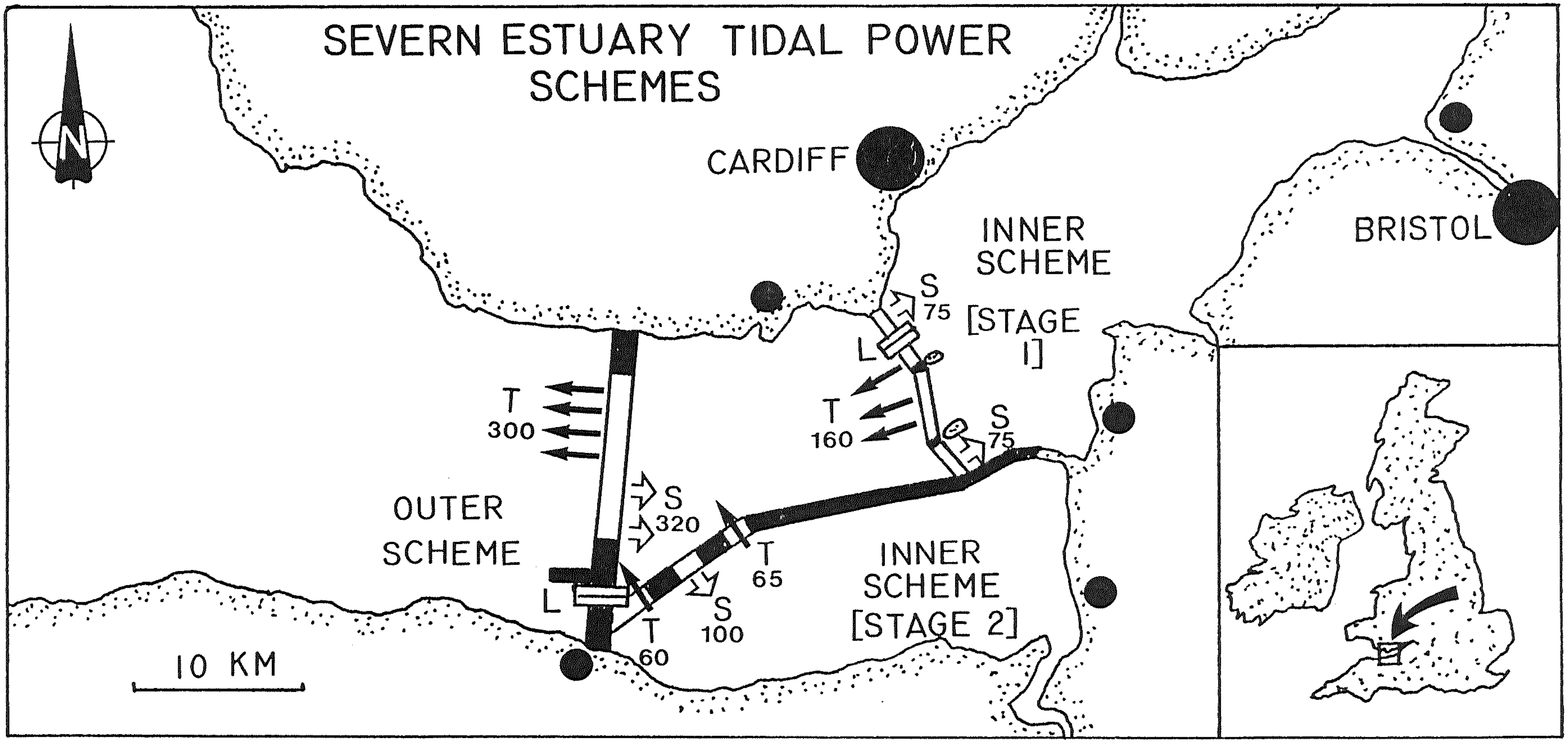
B) PLAN



DABORN FIG 1.


QUEBEC
NFL
NB
USA
NS
46
NEW
BRUNSWICK
PASSAMAQUODDY
BAY
BAY OF FUNDY
CUMBERLAND
BASIN
A8
MINAS BASIN
COBEQUID
BAY
B9
NOVA SCOTIA
ANNAPOLIS
50 KM
SITE KEY
ABANDONED
PROPOSAL
CURRENT
PROPOSAL
EXISTING PLANT
67
66
65
64
63
46
45
44

DABORN FIG. 2.


SEVERN ESTUARY TIDAL POWER SCHEMES
N
CARDIFF
BRISTOL
INNER SCHEME [STAGE 1]
INNER SCHEME [STAGE 2]
OUTER SCHEME
S 75
S 75
L
T 160
T 300
S 320
T 65
S 100
T 60
L
10 KM

DABORN FIG 3