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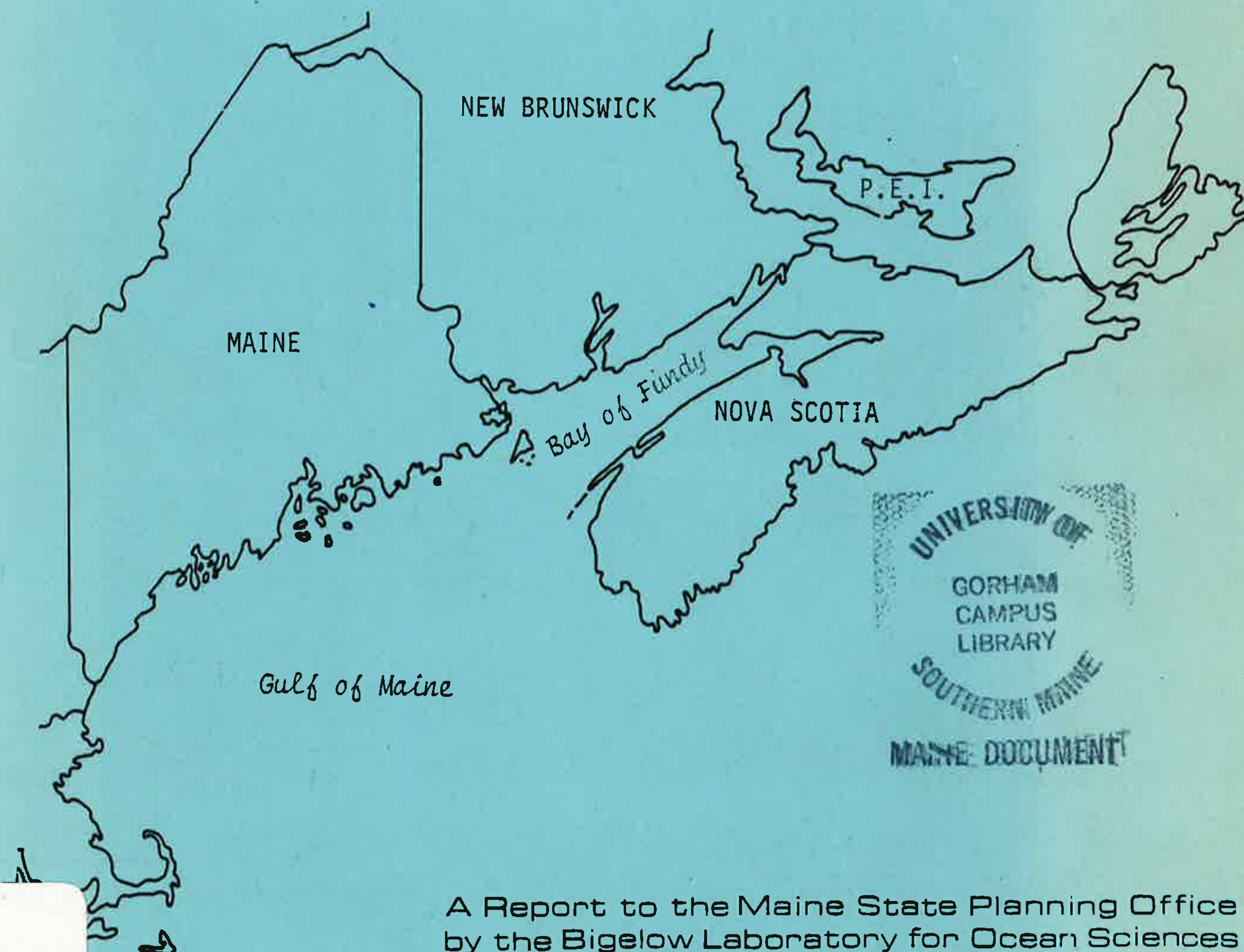
Fundy Tidal Power Development

Preliminary Evaluation of its Environmental Consequences to Maine



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A Report to the Maine State Planning Office
by the Bigelow Laboratory for Ocean Sciences

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. Larsen & J. A.Topinka, Editors

April 1984

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FUNDY TIDAL POWER DEVELOPMENT

Preliminary Evaluation of Its Environmental Consequences to the Resources of the State of Maine

A Report to the Maine State Planning Office
by
the Bigelow Laboratory for Ocean Sciences

April, 1984

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PREFACE

In 1982, the Tidal Power Corporation of Nova Scotia announced that the production of tidal power in the Bay of Fundy is economically feasible.

The Maine Legislature, concerned about the rise in sea level predicted by the Nova Scotians' scientists, instructed the Maine State Planning Office to examine the consequences of Fundy tidal power development on the coast of Maine. The State Planning Office subsequently contracted with the Bigelow Laboratory for Ocean Sciences in West Boothbay Harbor to review existing scientific knowledge of these consequences, and to identify what further research is needed better to understand them and their impacts. The Planning Office also formed a review committee of seven State natural resource agencies to comment upon the Bigelow Laboratory's work.

This report is the result of that effort. It is intended as a basis for further discussion among State and federal officials, the general public, and members of the scientific community, so that Maine may take a reasoned and informed approach to tidal power development in the Bay of Fundy.

The Bigelow Laboratory is solely responsible for its content.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

A. Introduction

Construction of a five-mile long tidal power dam in the Bay of Fundy is predicted to increase tidal range by approximately 10% in the Gulf of Maine. This alteration of tidal regime would produce some important physical changes in coastal and offshore regions. The broad scope of potential physical and biological influences on this large and productive region may include significant impacts on marine structures, activities and ecosystems and result in significant socio-economic impacts. The focus of this report is directed toward a preliminary examination of the environmental consequences associated with this 10% increase in tidal range.

A change in tidal range will not merely add to the tidal "noise" of the existing tidal regime, but will result in an important shift in tidal baseline conditions. While large natural changes in tidal range normally occur, they all contribute to variability around an average tidal range. The tidal amplification produced by tidal power construction is, however, different and important because it represents a one-way shift in average or baseline tidal conditions. Tidal effects, as on tidal current velocities, are also likely to be one-way shifts.

While some resulting environmental effects may be dramatic, other effects may be more subtle. If a resulting environmental impact is correctly viewed as the product of the magnitude of alteration and the area over which the alteration is experienced, many impacts may be important due to the vast size of the Gulf of Maine where tidal effects will be felt.

B. Tidal Power Construction

The Nova Scotia Tidal Power Corporation is seeking to construct a large tidal power dam in the upper reaches of the Bay of Fundy. In 1982, the Nova Scotian Tidal Power Corporation issued a revision of an earlier 1977 report entitled, of Fundy Tidal Power Update '82. While still in the process of site evaluation, it appears that the site in Minas Basin, Bay of Fundy, is presently under the most serious consideration. The proposed five-mile tidal dam located at site B9, in the Minas Basin of Nova Scotia, would be fitted with 106-140 turbines to produce 3800-5300 MW of electrical power.

The environmental considerations presented here are based upon the proposed construction at the B9 site in the Minas Basin. This construction would produce the greatest power and the largest change in tidal amplitude of any site under present consideration. There is also the possibility of dam construction at site A-8 in Cumberland Basin between Peck's Point and Boss Point in conjunction with B-9, and the potential addition of another dam at A-6 in Shepody Bay. The dams proposed at A-8 and A-6 are relatively small, but each could add approximately 6-8 cm to a 30 cm increase in tidal range produced in the Gulf of Maine.

Efforts are now being made by the Nova Scotia Tidal Power Corporation to secure approximately 100 million dollars for a 2-4 year

engineering and environmental study. This financing may become available early in 1984. A 10-12 year construction period would be commenced upon completion of the engineering environmental study. Although the 7 billion dollar construction costs remain to be financed, the latest feasibility study suggests that such a project is economically viable. According to George Baker, Executive Vice-President of the Tidal Power Corporation, there is an approximate 25% likelihood of project construction within the next few years. Mr. Baker suggests this probability increases to a level approaching certainty in an undefined "long-term." Present plans call for approximately 90% of the power generated to be exported to the U.S. The 1982 economic evaluation of the Nova Scotia Tidal Power Corporation determined that such a facility would have a benefit/cost ratio of 2.6-3.0 under present economic conditions. Construction costs are presently a major impediment to the project's initiation.

Interest in tidal power is not new. Over the past half century, large tides in the Gulf of Maine and Bay of Fundy have attracted interest as a potential power source for hydroelectric generation. Previous proposals have ranged in size from the 1800 MW Passamaquoddy Bay project, investigated by the U.S. and Canada through the International Joint Commission between 1956 and 1961, to the current 12 MW project at Half Moon Cove on Cobscook Bay in Washington County, conceived by the Passamaquoddy Tribal Council.

Until recently, none of these projects had proceeded beyond the planning stage. During the spring of 1984, a $46 million, 20 MW tidal power plant at Annapolis Royal on the southwestern coast of Nova Scotia, is scheduled for completion. Not only will this be the first operating

tidal power facility in the Western Hemisphere, it will also serve as a pilot project to test hydroelectric turbines and the feasibility of large-scale tidal development elsewhere in the Bay of Fundy.

C. Predicted Tidal Alteration

Following previous suggestions by several oceanographers that tidal range could be altered by large scale Fundy tidal power development, Dr. David Greenberg, from the Bedford Institute of Oceanography, together with Canadian colleagues, developed a tidal model which predicts that tidal power construction in the Minas Basin will alter tidal range in many regions of the Bay of Fundy/Gulf of Maine tidal basin. Although the model predicts that some areas would experience either a decrease in tidal range or no change at all, it also projects an approximate 5% increase in tidal range in the Bay of Fundy and a 10% increase for sites within the Gulf of Maine.

The same phenomenon of tidal resonance that gives rise to extreme Bay of Fundy tides will lead to an expanded tidal range in the Gulf of Maine following tidal power construction in Minas Basin. The world's largest mean tides are largely a result of resonance between the oceanic tidal period and the natural period of the Bay of Fundy and Gulf of Maine regions. Construction in the Minas Basin would shorten the 12.5 hr period of the Gulf of Maine/Bay of Fundy tidal basin, bringing it even closer to the North Atlantic M_2 tidal period of 12.42 hr. As the ratio of basin to tidal period approaches an optimum resonant ratio of 1, tidal range becomes extremely sensitive to relatively small changes in basin period, producing disproportionately large influences on tidal regime. For much of the Gulf of Maine, tidal power construction in Minas Basin would result in a 15 cm (6 in) elevation of Mean High Water,

and a 15 cm depression of Mean Low Water, with no change in mean sea level.

The precision of Greenberg's tidal prediction is central to all physical and biological alterations. This model is held in high regard by the oceanographic community and represents the best model of the Bay of Fundy/Gulf of Maine tidal regime and its behavior under a new configuration. Testing of Greenberg's model has suggested that the uncertainty of the new tidal regime is on the order of $\pm$ 10% of the predicted 30 cm (12 in) change in tidal range.

The presence of operating tidal power facilities provides no practical experience with far-field alteration of tidal regime or its environmental consequences. Due to the relatively small size of the largest operating tidal power facility at LaRance (240 MW), no changes in tidal regime were predicted or experienced.

D. Concerns for Maine

The Gulf of Maine would be vastly different were it not for tidal action. The ebb and flow of tides is without question an important feature of coastal Maine. Their rise and fall structure unique communities of intertidal plants and animals that are of considerable biological and economic value. But tides are more than merely a rise and fall of water level. Tidal action provides an important force which drives water movements in coastal and offshore regions. These water movements, in turn, exert profound influences on physical and biological regimes in the Gulf of Maine.

Because a change in tidal regime could have substantial impacts upon the environment, economy, and people of Maine, Governor Joseph E. Brennan requested that the State Planning Office (SPO) begin an investi-

gation of these potential effects and report to him with recommendations for further action, including the need for additional, detailed scientific analysis. In 1982, SPO contracted with the Bigelow Laboratory for Ocean Sciences to conduct a preliminary evaluation of the environmental consequences of Fundy tidal power development on the resources of the State of Maine. While the availability of such electrical power could provide a source of energy and reduce U.S. dependence on fossil and nuclear sources, the development of this energy source does not come without environmental consequences.

On the basis of the Canadian projections for tidal range and current amplification, this report concludes that the Minas Basin project would have potentially important physical, geological, biological and socio-economic consequences on Maine. This report identifies issues of concern, reviews available information and determines priorities for future research. The findings contained herein are preliminary and constitute neither a complete nor a definitive assessment of the effects of Minas Basin development. Additional, detailed investigation and analysis are necessary to determine precise impacts upon specific areas and resources.

E. Physical Consequences

A 10% increase in tidal amplitude will result in an approximate 10% widening of the intertidal zone and a concomitant loss of adjacent terrestrial and subtidal area. Our preliminary estimates suggest that through land submergence, higher mean tides will result in the loss of 17 km^2 (4200 acres) of coastal property and terrestrial habitat. Independent estimates suggest that tidal flooding may encompass in excess of 40 km^2 (10,000 acres). The low-lying southwestern sector of

the coast would receive the greatest flooding with much of this flooding likely to occur along high marsh areas. The combination of rapid land subsidence, rising sea levels, an expanding tidal range, and a sudden 15 cm increase in mean high water could result in extensive salt marsh erosion in northeastern and southwestern coastal areas.

Shoreline retreat will vary considerably, depending upon the slope of specific areas affected. Rocky shore communities will restabilize quickly, while marshes and mudflats may take many years to adjust. Although some preliminary estimates suggest that along the flat, sandy coast of York County, some beaches could retreat by 20 m (66 ft) over the next 50 years, other beach-building processes could offset this loss.

Increased tidal fluctuations would cause the saltwater wedge underlying coastal aquifers to rise. Fully one-quarter of Maine's coastal communities will experience a decline in drinking water quality due to the intrusion of saltwater into groundwater aquifers.

The increased tidal range would alter sedimentation patterns in tidal inlets. Natural inlets bounded by borders capable of being eroded would become wider. Inlets bounded by man-made jetties would become deeper and wave action within harbors would increase.

The 15 cm increase in high tides could add to water height during storm surges. This could more than double the frequency with which present "damaging" storm tide levels are reached. The water height produced by the 1978 nor'easter that caused $47 million in losses, now occurs about every 100 years. Under the new regime the same water height would be produced by lesser storms which occur about every 25 years.

Greater tidal amplitude will yield higher current velocities which will increase vertical mixing of the water column in coastal and offshore areas. This increased mixing will result in lower surface water temperatures and greater homogeneity in the water column.

Along some coastal regions, temperature of surface waters could be decreased by as much as $1^{\circ}C$ ($1.8^{\circ}F$) during summer. If widespread, this would result in lower air temperatures, a greater incidence of fog, and stronger onshore winds in summer.

Worldwide increases in mean sea level, rapid land subsidence in southwestern and northeastern Maine, and increasing high water levels due to natural tidal expansion are increasing high water levels at alarming rates, which in "downeast" (northeastern) Maine, are in excess of 1 cm/yr (0.4 in/yr). Many of the natural problems associated with increased flooding will be exacerbated by a 15 cm rise in mean high water due to tidal power construction. The expansion of tide range due to tidal power construction will, unlike most natural changes in sea level, produce the additional effects which result from a change in current velocities, vertical mixing intensities, water temperatures and circulation patterns.

F. Biological Consequences

The physical and environmental effects of the Minas Basin project would have a variety of effects upon coastal, marine and terrestrial biology. Without more detailed study, it is difficult to estimate the absolute magnitude of these changes; however, some general trends are evident.

Swifter tidal currents will result in greater flushing of estuaries. This could have several effects, both positive and negative.

The larvae of shellfish and other species would be dispersed over a greater area. This could lead to lower colonization by free floating shellfish larvae in some traditional shellfish beds. It may, however, result in the colonization of productive new areas, and the reseeding of still other areas which have been depleted or spoiled by past pollution. Increased flushing and vertical mixing could also enhance the growth of estuarine phytoplankton, macroalgae and marsh grasses which serve as food for estuarine fauna.

Increased flushing would also be beneficial in the event of pollution discharges by resulting in a faster dispersal of many types of pollutants. While higher current velocities would render spilled oil more difficult to contain or recover, spilled oil would be dispersed more quickly.

In offshore regions, increased vertical mixing in summer will result in the upwelling of deep water nutrients to enhance food production by phytoplankton. Where these phytoplankton are mixed to greater depths away from light, decreased growth may result. These events could have important fisheries benefits if primary production is significantly increased.

While increased tidal amplitudes may potentially produce effects upon the organisms which cause the "red tide" phenomenon, no quantification is advisable. It is, however, possible that increased tidal velocities could create a more conducive environment for the development and growth of these organisms by increased nutrient upwelling along frontal systems and could also transport red tide organisms further and faster, increasing the spread of red tide blooms.

Higher tides would bring greater quantities of seawater into estuaries, possibly disturbing the natural ecological balance for certain plant and animal species. These effects would be site specific, but an ecologically sensitive area, such as Merrymeeting Bay, could witness dramatic changes.

Lower summer water temperatures will have detrimental effects on various plant and animal species which approach their northern limit in Maine waters. Such animals include the American oyster and horseshoe crab. The migratory patterns of certain fin fish species like bluefish and menhaden might change due to lower water temperature. Finfish like the American shad would have their migratory patterns changed by the physical presence of the Minas Basin dam or could face damage by turbines. The predicted merging of vertically mixed areas over Georges Bank and Nantucket Shoals would also produce significant changes in productivity and influence local fish distributions. Higher tides and swifter currents would also enhance the growth of barnacles and other "fouling" species which damage physical structures and vessels.

G. Socio-economic Consequences

The physical and biological effects of Minas Basin would have significant impacts on the economy and culture of Maine. While only coastal areas would receive direct impacts, the entire State can expect to share in the results of these effects.

The loss of land due to the increased tidal range, and the real or perceived effects of damage from more frequent storms and flooding, will decrease the value of some coastal property, especially in southern Maine. Insurance costs and actual damages in such areas could total

millions of dollars. Diminished property values could result in reduced property tax revenues in some communities.

The addition of new intertidal area, however, such as clam flats, will enhance values in some communities. The faster dispersion of pollution would also benefit the environment and the economy and tend to offset other effects of the Minas Basin project.

Maine would also benefit from a new, predictable, environmentally clean source of energy which could replace some of Maine's dependence on fossil fuel and nuclear power. While the amount of electrical power available to Maine and its cost remain uncertain, large amounts of reasonably priced electrical energy would be extremely attractive.

Coastal tourism and recreation, which are vital to the State's economy, could suffer from poorer weather conditions such as increased fog, stronger sea breezes and lower air temperature, however, the magnitude of these changes cannot presently be determined. These meteorological effects, coupled with the lower low tides and swifter currents, will have detrimental effects on marine transportation. Docking and mooring will be more difficult, and the potential for accidents could increase. Swifter currents will also impede navigation, resulting in greater fuel consumption. Harbors may be altered by changes in patterns of sedimentation, and structures, such as piers and docks, will be subject to more damage from high water, storms, wave action and "fouling" organisms.

The tides, storms and currents will affect many roads, bridges, seawalls and various other physical structures. Some, such as the bridge at Rutherford Island in South Bristol, may have to be relocated or reconstructed. Others will be subject to greater damage. Intrusion

of saltwater into wells and effects upon services such as sewage treatment facilities would have serious implications for local governments along the coast.

Many effects on fishing are difficult to anticipate without high resolution predictions of physical tidal influences and a better understanding of present tidal influence on fisheries. Some broad fisheries predictions are, however, possible. The resulting increased intertidal area, greater nutrient availability, and enhanced pollution dispersion may be beneficial to some species, especially shellfish. However, shifting beds and the dispersal of larvae could dislocate many productive shellfish beds. Potentially increased red tide occurrence would restrict catches of clams, mussels and oysters. The potential catch of finfish, such as the American shad, which normally migrate through Minas Basin, may also be decreased.

The lower water temperature at the surface in summer may limit the catch of some surface-dwelling finfish. In some areas, swifter currents will make fishing more difficult and raise fuel consumption. Damage to vessels and structures from storms, wave action and "fouling" species, would also increase.

Offsetting these effects is a potentially greater supply of food due to increased plant growth both in coastal and offshore areas. Such increased productivity could translate into greater fish catches of species whose populations are limited by food availability.

H. Recommended Actions

An examination of the potential effects of an increased tidal amplitude on Maine emphasizes our need to know more about the fundamental mechanisms that are important to estuarine and marine systems. It

is important to realize that a knowledge of the environmental effects is basic to our understanding of major economic influences and must be examined together with socio-economic effects. Research needs and options are considered in detail in Section V. Research Needs, of this report.

While definitive predictions are beyond the scope of this report, this document establishes a focus on research which will yield the best predictions of tidal effects. Research proposed here will also contribute to a greater understanding of the ways in which water levels and water movements structure the Gulf of Maine and its coastline. Such research will also need to be performed if we are to better anticipate the effects of naturally occurring levels of land subsidence, rises in sea level and an expansion of tidal range.

The following presents a brief list of primary and secondary recommendations. It is suggested that many of these areas of concern may be dealt with in an integrated study plan as described in Section V.

1. Primary recommendations

   1. Tidal predictions are central to all environmental effects. The validation of Greenberg's tidal predictions by the construction of another major tidal model is viewed as unnecessary. It is, however, suggested that physical oceanographers, other scientists and representatives from the Army Corps of Engineers participate in a 2-day workshop to examine the Greenberg model and issue a collective report on the adequacy of Greenberg's model to produce tidal predictions. This rapid and low cost mechanism serves to examine Greenberg's predictions and increase the understanding of those that would use such predictions. It if could be demonstrated

that the construction of another, more precise tidal model is both necessary and possible, such an effort should be undertaken. This is one of the important first steps and should be undertaken immediately.

2. It would be most valuable to use the Greenberg model to obtain tidal predictions on a finer scale in order to provide more detailed tidal changes which are required for the prediction of other environmental alterations. This investigation should be accompanied by efforts to model tidal responses of individual embayments.

3. The degree to which an altered tidal amplitude will change other primary physical features must be known. Using the Greenberg model, in conjunction with coastal models, predictions should be made of current velocities, vertical mixing intensities, water temperatures and circulation patterns on the same detailed scale used for tidal amplitude predictions.

4. It is necessary to quantify changes in intertidal area due to tidal flooding. This study should include examination of associated habitat and biological changes. Potential changes in beach, salt marsh and mudflat configuration should also be examined.

5. The phytoplankton production that drives biological systems in coastal and offshore regions may be altered by a new tidal regime. The extent to which this crucial production process may be changed must be determined.

6. Increased tidal flushing and vertical mixing will occur in estuaries. These effects may alter temperature, salinity, and primary production, resulting in changes in biological distribu-

tions. The dispersion of pollutants will also be facilitated. It is necessary to understand the magnitude of these changes.

7. Many economic impacts can be identified at this time. Case studies in two or three coastal communities should be made by a multi-disciplinary team to develop a deeper understanding of the economic consequences to various sectors of the community.
8. Tidal perturbations caused by tidal power development must be examined in the context of present sea level rises and the expansion of tidal range.
9. The loss of migratory species like the American shad due to dam design and operation should be quantified.

2. Additional recommendations

1. The ways in which dam design and operation may lessen potential tidal enhancement during storm surges should be examined.
2. In the event of unforeseen or unacceptable environmental responses, the extent to which tidal power operation could be routinely changed to lessen these responses should be known.
3. The rate of tidal range alteration during dam construction must be calculated from a knowledge of how quickly this construction will change the period of the Gulf of Maine/Bay of Fundy tidal basin period.
4. Air/sea interactions should be evaluated to determine climatic changes due to lower water temperatures during summer.
5. It must be understood how storm damage will be altered by a new tidal regime. An identification should be made of the roads, bridges, railways, utilities, and dwellings which are located near

high water levels and subject to natural tidal flooding and increased storm damage.

6. The physical and biological consequences of natural variability in tidal cycles should be better understood.
7. The problem of increased intrusion of salt water into wells should be quantified.
8. The physical and biological effects of plant closure must be considered.

Acknowledgements

The material, ideas and concepts contained in this report were developed over the past three years. During that period many persons contributed toward their evolution to their present form. The authors acknowledge that the effort could not have been successful without the willing cooperation of these people.

The Canadian tidal power community was especially cooperative and supportive. Special thanks go to David A. Greenberg of the Bedford Institute of Oceanography who introduced us to farfield tidal power effects and patiently answered our many questions. Likewise, George C. Baker of the Tidal Power Corporation provided us with information, guidance and advice essential to the successful completion of this report. Other Canadian scientists who made significant contributions to our understanding include Graham R. Daborn of Acadia University, Donald C. Gordon and Carl Amos of the Bedford Institute of Oceanography, Christopher Garrett of Dalhousie University and Michael J. Dadswell of the Canadian Department of Fisheries and Oceans.

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I: INTRODUCTION

A. PURPOSE OF STUDY

Oceanographic modelling undertaken as part of the planning process for Fundy tidal power development indicates that the tidal regime of the entire Gulf of Maine could be altered by barrage construction at the head of the Bay of Fundy. Modification of the tidal regime will have profound effects on the physical and biological processes active in the coastal zone. These modifications, coupled with the naturally occurring rise in sea level, and the natural increase in tidal range, will have serious environmental and economic implications in the decades ahead. The degree to which the environmental changes on the Maine coast can be accurately anticipated will determine the extent to which economic damage can be avoided or reduced.

The principal goals of this report are to provide knowledge necessary for the prediction of environmental alterations associated with tidal power development at the head of the Bay of Fundy, and to develop a research plan for the prediction of tidal effects. This information is required for the multitude of large and small decisions which must be made concerning the varied uses of the coastal zone. Do we locate a road or a building at a certain elevation or, given the knowledge of the rising sea level and increasing tidal range, do we prudently locate it a foot or two higher? This is an example of a situation where foreknowledge of environmental conditions can make the difference between a certain economic disaster in the near future and an investment which will realize its full potential. Other decisions have to be made concerning disposition of public and private lands, waste disposal, fishery and agricultural developments, groundwater resources,

etc. These routine decisions have to be made regardless of whether or not Fundy tidal power becomes reality. The decisions might be slightly different, however, if Fundy development is considered. Alterations in planning decisions made at this time, in light of the potential for Fundy tidal power, may save considerable money and hardship in the future.

The utility of the present exercise is not lost if the decision is made not to go ahead with Fundy tidal power. Due to naturally rising sea level and increasing tidal range, many of the far-field environmental consequences due to flooding now identified with Fundy tidal power development may ultimately be realized. It is, therefore, prudent to consider what their manifestation implies for the coastal resources of Maine. It must be remembered, however, that the changes associated with Fundy tidal power development will occur <u>in addition to</u> natural changes and hence will accelerate and exacerbate the environmental consequences.

The first tasks in making decisions on environmental problems are to identify the problems and quantify the probable impacts. To the extent possible, we have identified the specific environmental consequences of Fundy tidal power development on the coastal environment of Maine. We have given initial consideration to the entire spectrum of potential environmental changes, both detrimental and beneficial, which are deemed at all possible by the scientific community. We have put these environmental consequences into a socio-economic context and have suggested further research to reduce the predictive uncertainty surrounding many of the more important issues.

The far-reaching and basic nature of tidal interactions with the coastal zone produces a study area of amazing scope when the tidal regime is changed. The major limitation of this study is the short time available to evaluate all of the aspects of the problem. Thus, few areas were researched to the complete satisfaction of the scientists involved or the users of the report. This limitation is offset somewhat by the setting of priority areas of study, such as potential for increased erosion and changes in biological productivity, by the State Planning Office and other interested agencies. Even so, few of the issues raised could be completely resolved.

Another major limitation of the study involves the lack of fundamental understanding of several basic processes in the Gulf of Maine. Reliable predictions of tidal power consequences cannot be made when the normal situation is poorly understood. Much basic research is needed in the Gulf of Maine if this and other impending environmental impacts are to be accurately anticipated.

B. THE ADVENT OF TIDAL POWER

The generation of electricity by turbines turned by tidal water is a concept that may be coming of age. A century ago many coastal mills were driven by tidal energy but the practice was discontinued with the development of engines and inexpensive fossil fuels. However, rising energy costs resulting from increased fossil fuel costs, along with concern about the safety of nuclear power, has sparked a renewed interest in developing tidal power resources. Tidal energy has several advantages over conventional energy sources. It is a renewable source of energy that is not influenced by seasonal water levels, floods, or

droughts as is conventional hydropower. Although most operational modes only produce power on an intermittent basis, requiring tidal power facilities to be integrated with other systems, power production is predictable years in advance. Since it uses no fuel, problems associated with fuel acquisition and waste product disposal are avoided.

Although interest in the potential for tidal power has been manifested periodically, there has never been such a high degree of activity as there is today. The 240 MW LaRance project on France's Brittany coast has been successfully producing electricity since 1967. Other sites are presently being evaluated along the coasts of Brittany and Normandy. The British are continuing their consideration of the Severn Estuary barrage and have already completed extensive environmental studies. Major sites in Argentina, Australia, India and Korea have received preliminary evaluations and a demonstration project has been built in Russia.

Due to the relatively small size of existing tidal dams and the configuration of the areas in which they lie, none produce, or would be anticipated to produce, a significant alteration of tidal regime outside the dam. Therefore, while tidal dams are in existence, their presence provides no practical experience with far-field effects.

In North America, interest in tidal power is high in the Gulf of Maine-Bay of Fundy region (Fig. 1). There are at least three projects being studied on the United States side of the border. The Passamaquoddy Indian Tribe has done extensive studies on the potential for a 12 MW tidal unit in Halfmoon Cove in Perry, Maine. Also in Cobscook Bay, the U.S. Army Corps of Engineers is evaluating several possible tidal dam configurations and operating modes. A very small, private initia-

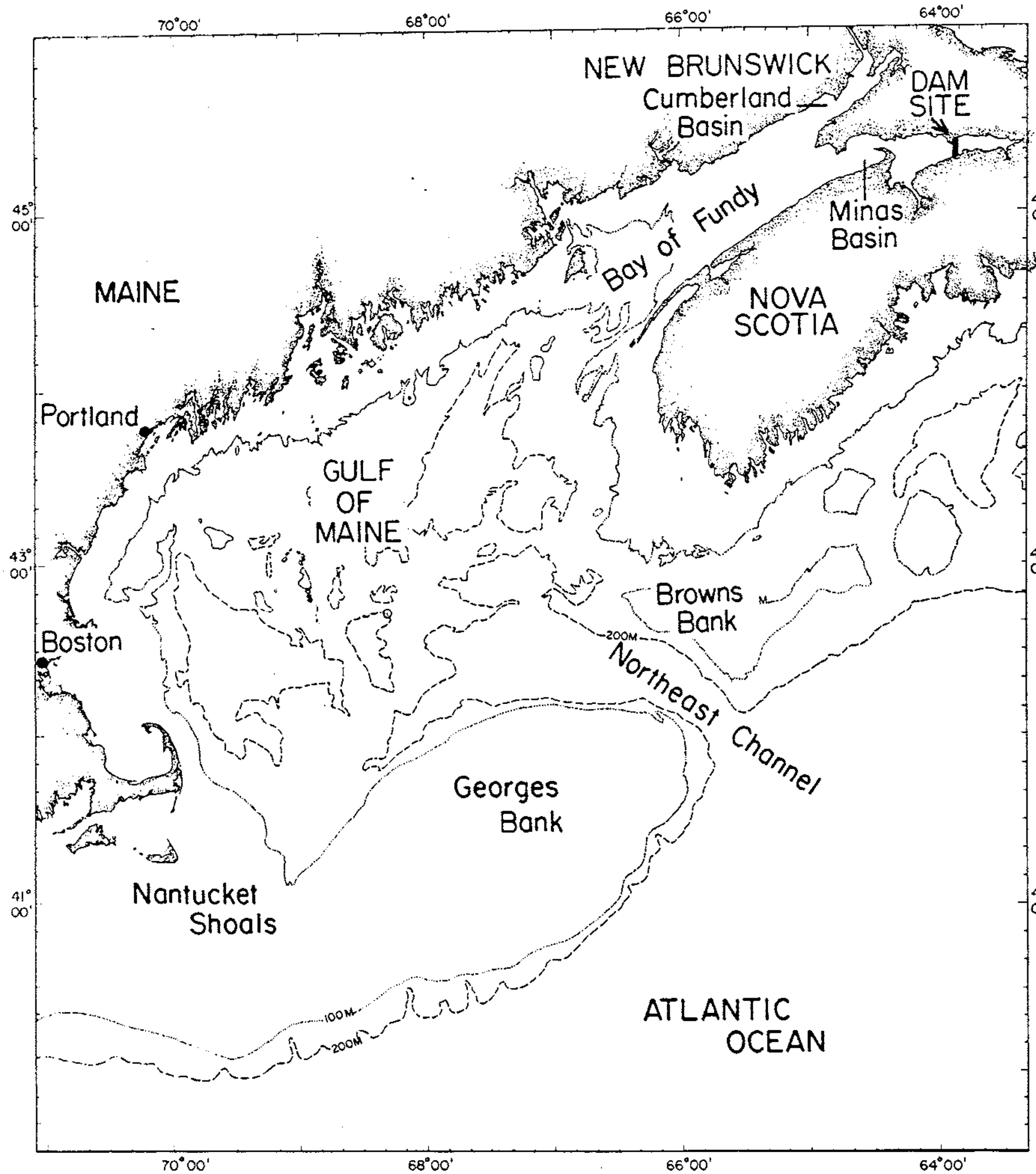

Fig. 1 - The Gulf of Maine - Bay of Fundy region.

tive is underway in central Maine on the island of Vinalhaven could result in the first active tidal power plant in the U.S. In addition, the Maine Office of Energy Resources and State Planning Office are surveying the Maine shoreline to determine its potential for small scale tidal power development.

The vast majority of North American interest in tidal power during the last two decades has been focused on the upper Bay of Fundy. The first tidal power plant in the western hemisphere will go on line at Annapolis Royal, Nova Scotia in the spring of 1984. This project consists of a 20 MW low head Straflo turbine fitted into a pre-existing barrage. Its purpose is to demonstrate the utility of the turbine in the marine environment. Construction costs using this type of turbine are 10-15% less than those associated with more conventional low head turbines, so the success of this pilot project could have a significant impact on the feasibility of large scale developments. Several sites for large scale tidal power developments have been studied in the upper Bay of Fundy. For the last two years extensive and intensive technical, economic and environmental consideration has been directed at site B9 in the Minas Basin (Fig. 1). This site, with a potential capacity of up to 5,300 MW, may be the world's first "mega-project." It is the focus of this report.

Construction at site B9 would produce the greatest power and the largest change in tidal amplitude of any site under present consideration. There is also the possibility of dam construction at site A-8 in Cumberland Basin in conjunction with B-9, and the potential addition of a minor dam at A-6 in Shepody Bay. Dams at A-8 and A-6 are relatively small, but each could add approximately 6-8 cm to a 30 cm increase in

tidal range produced in the Gulf of Maine and would result in an increase in the intensity of environmental responses. As their immediate addition is not likely, environmental predictions presented in this report are based on construction at Minas Basin alone.

1. TIDAL POWER THEORY AND OPERATION

The concept of tidal power is simple. In its most basic form (Fig. 2), an impoundment is allowed to fill on the rising tide through filling gates or sluices. When the tide reaches its maximum height the sluices are closed. As the tide falls, the tidal pool is held at this level until a sufficient water level differential, or head, develops between the tidal pool and the sea. A head of about two meters is considered a minimum. At this point, the impounded water is drained from the pool through turbines which generate electricity. This process continues as the tide ebbs as long as sufficient head exists. Near low tide to mid-flood stage the turbines are closed and, when the rising tidal level equals the level in the pool, the sluices are opened and filling commences again. This process is repeated with each tide, i.e. 705 times a year.

The above operation is called a single effect, high pool system; single effect means that power is generated only on one phase of the tide and high pool indicates that it is the water level of the impounded pool is maintained higher than instantaneous sea level. This is only one of several operating modes that can be used singly or in combination with one another. It is, however, the most commonly proposed operating mode because it is the most inexpensive to build and the easiest to

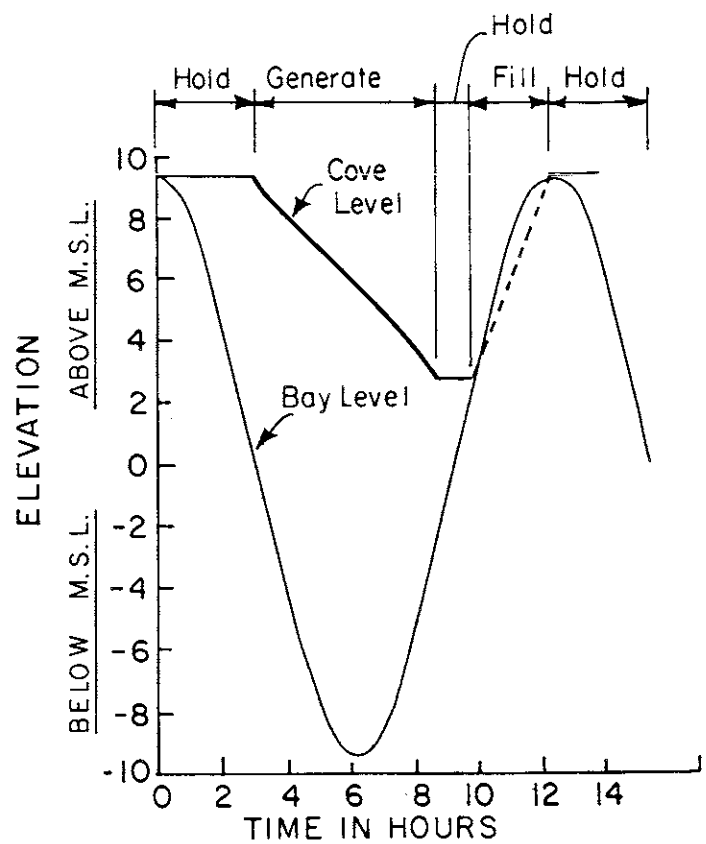

Fig. 2. Operating phases of a single effect, high pool tidal power facility.

operate. Its major disadvantage is that electricity is produced only about 50% of the time and production is often out of phase with demand.

A single effect, low pool operation is created when the gates are closed at low tide allowing the level of the sea to exceed the level in the basin. Electricity is generated by running water through the turbines from the sea into the basin. This procedure produces less electricity than a high pool system because the head cannot be controlled. The environmental effects are also probably less desirable. Its major advantage is that the production of electricity is 180° out of phase with a high pool system. Therefore, a low pool operated in conjunction with a high pool, can generate electricity almost continually. A recent feasibility study showed that if a low pool system were to be built in one of the several arms of the Cobscook Bay to complement the proposed Halfmoon Cove high pool system, electricity from tidal energy would be available 96% of the year.

With the use of reversible turbines a double effect tidal plant can be realized. Here, electricity is generated on both the rising and falling tides. Production ceases only near the turning points of the tide when little or no head exists. Due to the physics of the system a double effect operating mode produces less total energy than a single effect high pool system, but the production is more nearly continuous and, hence, is more easily integrated into an electrical grid. The major disadvantage of a double effect system is the higher cost of the more sophisticated turbines. This results in about a 20% increase in the cost of electricity. The one major existing tidal facility in the world today, the LaRance project in France, has double effect capability.

The above are the three basic operating modes of tidal power plants. Several variations exist. The actual operation may be very complex and involve switching of operating modes to better couple production to demand or to take maximum advantage of tidal periodicities.

For further information on the tides and tidal power the reader is referred to:

> Introduction to Tides: The Tides of the Waters of New England and New York by A.C. Redfield (Marine Science International)
>
> Tides and the Pull of the Moon by F.E. Wylie (Stephen Greene Press)
>
> Tidal Energy by Roger Henri Charlier (Van Nostrand Reinhold)

C. SHORT BACKGROUND ON THE PROPOSED FUNDY PROJECT

The extremely large tides and topography of the basins at the head of the Bay of Fundy, as well as their relative proximity to power markets, make these sites ideally suited for tidal power development. Several sites in the upper Bay of Fundy have been evaluated at various times for almost 20 years. In 1969, the Atlantic Tidal Power Programming Board (ATPPB, 1969) concluded that tidal power was not economically feasible under the existing conditions but that it might be if:

1. interest rates dropped;
2. a breakthrough occurred in construction costs or turbine costs;
3. pollution abatement requirements magnify the costs of alternative sources; or
4. alternative sources become depleted.

By 1972 sufficient changes had occurred in these factors and a major evaluation study was instituted by the governments of Canada, New Brunswick and Nova Scotia. The conclusions of the resulting 1977 report (Fundy Tidal Power Review Board, 1977) showed that at least two sites, B9 in Minas Basin and A8 in Cumberland Basin, had a benefit to cost ratio of 1.2 and therefore were approaching economic viability. Since 1977, technology, energy regulation policies and energy costs have changed even further. Interest and support for tidal power development has also shifted from New Brunswick to Nova Scotia. The need to raise capital has turned attention from the Cumberland Basin site, most highly recommended by the 1977 study, to a larger Minas Basin facility (possibly in conjunction with that of Cumberland Basin) which can produce excess power for export and encourage U.S. investment.

An update of the economic portions of the 1977 report was funded in 1981. This report, entitled "Fundy Tidal Power Update '82" (Tidal Power Corporation, 1982), contains the most favorable economic forecast for tidal power to date. Three factors contribute to this:

1) obviously, but not exclusively, the increased cost of energy generated by other methods.

   The value of tidal power is not that it replaces the need for construction of other generation plants, but that it replaces fuel costs. It is only the displaced fuel costs that are used in the economic comparisons.

2) changes in marketing strategies.

   In 1977 it was assumed that the electricity should be used principally in the Maritimes. This assumption was changed in

1982 allowing projections of energy needs and fuel costs in New England and New York to be used.

3) design changes.

Tidal power is capital intensive because of construction costs. Advances in turbine technology and modified construction procedures can shorten the construction period and produce electricity two years before the date projected in 1977.

Using conservative figures for energy needs, the cost of alternative fuel and construction costs, the 1982 report found the most efficient system to be a 4800 MW plant with the power distributed 10% to the Maritimes, 45% to New England and 45% to New York. The benefit to cost ratio then falls between 2.6 and 3.0 which makes this an economically attractive project.

The one remaining hurdle seems to be raising capital. Construction cost is estimated at 7 billion Canadian dollars in 1983. Predicted interest levels may increase the cost to 22 billion dollars over the 10 year construction period. To raise this money, proponents of tidal power must compete in a capital limited economic climate with other proposed large scale energy projects including increased nuclear options, hydropower in Quebec and offshore gas. In the next decade or two it would seem likely that only one of these major energy resources could be fully developed. At this time, it is not clear which resource that will be. Supporters of tidal power, however, believe Fundy tidal power economics are so favorable that it is a question of when, not if, the power potential of the upper Bay of Fundy will be harnessed.

D. OCEANOGRAPHIC SETTING OF THE GULF OF MAINE

1. PRESENT CONDITIONS

In order to appreciate the environmental implications of Fundy tidal power developments to the State of Maine, it is important to understand the Gulf of Maine and its tides. At the sea surface, the Gulf of Maine has the shape of a great horn, extending northeastward from the bottom of its broad mouth at Cape Cod to its split tip at the head of the Bay of Fundy (Fig. 1). But its sea surface shape is deceiving. Not far beneath the surface, three vast barriers - Browns Bank, Georges Bank and Nantucket Shoals - extending together in a broad arc from the Hatteras/Cape Cod Shelf to the Scotian Shelf, separate much of the Gulf's water from the open Atlantic Ocean. As a result, the Gulf of Maine has some characteristics of an inland sea. Its only deep water connection with the Atlantic Ocean is the Northeast Channel, which is approximately 40 km wide and lies between Georges and Browns Banks. The much shallower Great South Channel separates Georges Bank from Nantucket Shoals.

Among the Gulf's most striking characteristics is its tidal regime. Tidal range increases continuously from its mouth to its head where, at Burntcoat Head in Minas Basin, the largest mean tidal range in the world, 11.7 m, is recorded. The extreme vertical changes in tide level in the upper Bay of Fundy provide the potential for the economical extraction of large amounts of hydroelectric power.

Because of their great amplitude, the Gulf of Maine/Bay of Fundy tides have long interested oceanographers. Like coastal tides everywhere, the Gulf of Maine tides are not the direct result of the tide-producing forces of the moon and the sun. These forces do act

directly on the water of the Gulf, of course, but the total mass of the Gulf of Maine is too small for much energy to be transferred in this manner. Rather, the source of the Gulf's tidal energy lies in the tidal regime of the open ocean. The mean range of the Atlantic tide at the mouth of the Gulf is less than one meter. Its major constituent is the lunar semidiurnal, or M_2, constituent which has a period of 12.42 hours.

The key to understanding the vastly greater tides within the Gulf of Maine/Bay of Fundy system lies in the fact that the system's "free" period of oscillation is close to the 12.42 hour period of the semidiurnal tide. By the "free" period of a system is meant the period at which it will oscillate naturally if first given a push and then left alone. Just as the free period of a pendulum's swing depends upon its length, so the free period of a body of water depends upon its geometry, its horizontal and vertical dimensions. Of course, when pushed not once, but regularly, as the Gulf of Maine is by the ocean tides, the body of water oscillates, not at its own "free" period, but at the period of the pushes, the "forced" period. However, when its free period is close to, or the same as, the forcing period, energy is retained within the system and the amplitude of the oscillation becomes large. In this condition, called "resonance," only a relatively small amount of input energy is needed to maintain the large oscillations.

Resonance has been postulated by a number of investigators as an explanation for the large tidal ranges in the Gulf of Maine/Bay of Fundy system. Proudman (1953) calculated the free period of the Bay of Fundy alone to be 11.1 hours and assumed that it was forced by semidiurnal tides at the mouth of the bay. Later, as a result of studies by Rao (1968), Duff (1970) and Garrett (1972), it was found that Proudman's

calculated free period was too large for the Bay of Fundy alone, and that the Bay of Fundy and the Gulf of Maine combined to form a single oscillating system. Garrett (1974) calculated the fundamental free period of this system to lie between 12.4 and 13.0 hours. The most recent estimate is that by Greenberg (1979) who found the free period of the Gulf of Maine/Bay of Fundy system to be 12.5 hours.

Summarizing, tidal range increases by more than a factor of 10 from the mouth of the Gulf of Maine to its head in the upper Bay of Fundy. This great amplification is the result of near-resonance between the fundamental free period of oscillation of the Gulf of Maine system, approximately 12.5 hours, and the period of the open ocean tide which forces it, 12.42 hours. It is especially significant that the free period is greater than the forcing period (Garrett, 1974), for the free period can be reduced by the construction of a tidal barrage at the head of the Bay of Fundy resulting in increased resonance and therefore enhanced tides.

2. GREENBERG MODEL

Dr. David A. Greenberg of the Bedford Institute of Oceanography, has studied the Gulf of Maine/Bay of Fundy tidal regime, and the affect of tidal power development on it, for many years (e.g., Greenberg, 1969, 1975, 1976 and 1977). His recent paper, "A Numerical Model Investigation of Tidal Phenomena in the Bay of Fundy and Gulf of Maine" (Greenberg, 1979) updates the earlier work. Using the finite difference method, he applied the equations of continuity and motion through a grid with progressively smaller mesh size from the lower Gulf of Maine to the upper Bay of Fundy. Coriolis acceleration and quadratic friction terms

were included. The open boundary input consisted of a pure M_2 tide with the characteristics based on historical and recent data. The coefficient of friction and the depth of the Gulf of Maine were adjusted to produce the best fit to observed tides at 74 stations. It was the model goal to match observed tides within 15 cm for amplitude and 5° for phase, and this goal was generally met.

3. PREDICTED TIDAL RANGE CHANGES

It is to be expected that if the dimensions of the Gulf of Maine system were altered, as they would be by the construction of barriers for the purpose of hydroelectric power development, the tidal regime would also be altered. The barriers would reduce the size of the Gulf of Maine-Bay of Fundy tidal basin and therefore the free period of the system. Since the existing free period of the system is nearly resonant with, and slightly greater than, the M_2 forcing period, the barriers would be expected to cause an increase in tidal range throughout most of the system. In order to evaluate such effects, Greenberg ran his numerical model as calibrated, with modifications introduced to simulate the changes due to proposed barriers. In the case of a barrier which encloses Shepody Bay, the model showed an increase in tidal range for the Maine coast of less than 10 cm. However, a barrier in the upper Minas Basin would increase the range by 28 cm at Portland Harbor and 30 cm at Boston (Fig. 3). For the purposes of this study, it will be assumed that an increase of 30 cm would occur along the entire coast of Maine. This represents approximately a 10% increase in tidal range.

How realistic are the predictions based on the Greenberg model? This question is central to the concern about Fundy tidal power. It is

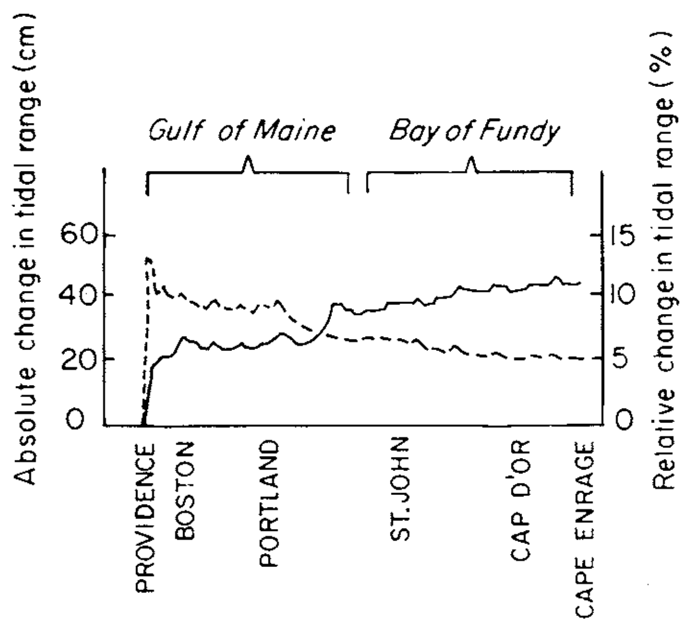

Fig. 3. Predicted absolute (——) and relative (---) change in tidal range in Gulf of Maine and Bay of Fundy. Note that amplitude is equal to one half the range (modified from Fundy Tidal Power Review Board, 1977).

also not a simple question, and a complete answer to it is beyond the scope of this project. During our interviews (see Methods section, below), modellers were asked their opinions of the adequacy of the model and the accuracy of its predictions. The Greenberg model is held in very high regard in the scientific community, and criticism of it tended to be on a detailed rather than conceptual level. A letter requesting evaluation of the model and three representative responses are included as Appendix I. It should be noted that several of the suggestions for improvement, such as a finer grid size and studies of residual currents have been done or are in progress.

Over what period of time would this increase occur? In answer to that question, asked in reference to the tidal hydroelectric facility presently proposed for the upper Minas Basin, Mr. George C. Baker, Executive Vice-President of the Tidal Power Corporation, estimated that the increase would take place gradually (although not steadily) over a period of approximately 5 years as construction gradually blocked tidal flow. Thus we calculate, as a first approximation, that tidal range would increase along the coast of Maine at a rate of about 6 cm per year, and that the mean high tide level would increase at a rate of about 3 cm per year, over the 5-year period. Dr. H.G. Tolland, a modeller on the Severn estuary project has a slightly different opinion, although it must be realized that he is not as familiar with the Fundy proposals. Dr. Tolland suggests that the tidal changes will approach a threshold effect, i.e. during construction little change in tides will be noted until a certain point during closure when the system will suddenly and rapidly switch to another equilibrium. Knowing the rate of

change is important because it will determine the severity of response of several physical and biological processes.

It is useful to compare these estimates with natural tidal variation and the existing rates of change of mean high tide in Maine. Annual mean sea level variation of ± 3 cm is not unusual for the coast of Maine, and similar variation is common between monthly mean sea levels (Permanent Service for Mean Sea Level, 1977). Tidal records obtained over a 50-year period indicate a mean sea level rise of about 3 mm/yr in Maine (Hicks, 1978). More recent evidence suggests that this may be much higher in some regions due to crustal warping. Land subsidence of up to 9 mm/yr has been observed in "downeast" (northeastern) Maine (Tyler, 1980).

Increase in sea level, rapid land subsidence in some coastal areas of Maine, and expanding tidal range are increasing high water levels is in excess of 10 mm/yr in some coastal areas. "Greenhouse" effects due to the melting of snow and ice, and the thermal expansion of the oceans are projected to rapidly accelerate sea level rise in the next century (Hoffman et al., 1983). The resulting natural problems will be exacerbated by a 15 cm rise in mean high water levels due to tidal power contruction.

Present rates of water level changes and tidal power influences are similar in that they raise the level of mean high water to result in coastal flooding and impacts associated with this flooding. Flooding influences must, therefore, be examined irregardless of tidal power construction.

Important differences also exist between natural sea level rises and those rendered by tidal power construction. First, the rises associated with tidal power will be relatively sudden and of large

magnitude, possibly resulting in the inability of coastal environments such as salt marshes to keep pace with these rises. Secondly, natural rises in mean high water levels are primarily the result of relative increases in mean sea level. Tidal power alterations, however, will not change mean sea level, but will change tidal range. It is important to recognize that an increase in sea level will be different from an increase in tidal range. As stressed in this report, many important impacts such as those induced by primary changes in current velocities, vertical mixing intensities, water temperature, and circulation patterns, are the result of an increased tidal range. An equivalent 15 cm rise in mean sea level alone would not produce these effects.

4. PREDICTED TIDAL CURRENT CHANGES

As tidal range is increased, tidal currents will also increase as a larger volume of water will be moved. While accurate predictions do not exist for the increase in tidal currents, current change may well be on the same order as for tidal range, i.e. about a 10% increase for much of the Maine coast. Increased tidal currents, resulting from an increased tidal amplitude, encounter friction as they move over the bottom. Some of this tidal current energy becomes dissipated as turbulence or mixing. In regions which become stratified, an increased tidal current velocity could increase mixing of surface or bottom waters. Decreases in summer surface water temperature on the order of $1^{\circ}C$ (Garrett, 1977) might result from enhanced, but not dramatically altered vertical mixing (Garrett et al., 1978).

II: METHODS

A. CONCEPTUAL FRAMEWORK

The most difficult task of this undertaking was to establish a comprehensive framework in which physical, biological and socio-economic issues could be considered while giving the reader sufficient detail without being excessively redundant.

After several iterations, the most efficient approach seemed to be to separate the physical and biological changes from the socio-economic consequences. Using this approach all the changes in the environment are explained in Part III of this report. In principle, these are the changes that would occur whether or not the coast of Maine was inhabited by man, e.g. changes in currents, sedimentation patterns, temperature, etc. How these changes manifest themselves in human terms, i.e. the socio-economic consequences, are presented in Part IV.

B. INFORMATION GATHERING

Once the conceptual framework was in place, the team began to gather and assimilate all of the relevant information available. In addition to their own acquired knowledge, three major sources of information were employed. First, computer searches of appropriate abstracting files were instituted. This produced lists of hundreds of articles and reports on tidal power and environmental studies. Secondly, using leads gained from the computer searches and existing knowledge of scientific literature, pertinent documents were acquired. Many of these were in the so-called "gray literature" and hence were not available through the computer searches. (Copies of the computer searches and much of the literature used can be examined at the Bigelow Laboratory.)

Personal interviews were a very important part of the information gathering procedure. Much of the information pertaining to the far-field effects of Fundy tidal power is very recent and state-of-the-art in nature. A great deal of it is yet to be published and much of even the most recent published material is already out-of-date. Over one hundred people were interviewed in the course of this study. Several people were interviewed a number of times as issues changed and additional knowledge became available.

III: PHYSICAL AND BIOLOGICAL CONSEQUENCES

A. TIDAL RANGE CHANGES

1. CONSEQUENCES OF ABSOLUTE CHANGES IN TIDAL RANGE

a. Expansion of intertidal area

Maine possesses an extensive and convoluted marine and estuarine shoreline totaling approximately 6705 km (Topinka and Korjeff, 1981). The predicted increase in tidal range will produce some significant changes along the coast especially in terms of intertidal area. Figure 4 illustrates the relationship between shoreline slope, the increase in intertidal area and the degree of land loss. It is most significant that shoreline changes are minor until shoreline slopes fall to approximately 10°. As one approaches a slope of 1° intertidal areas are rapidly expanded to the extent that a 30 cm increase in tidal range will increase the intertidal zone by almost 18 m and will push land borders back by approximately 9 m. In many salt marsh regions slopes may be considerably less than 1° and may have associated land borders recessed

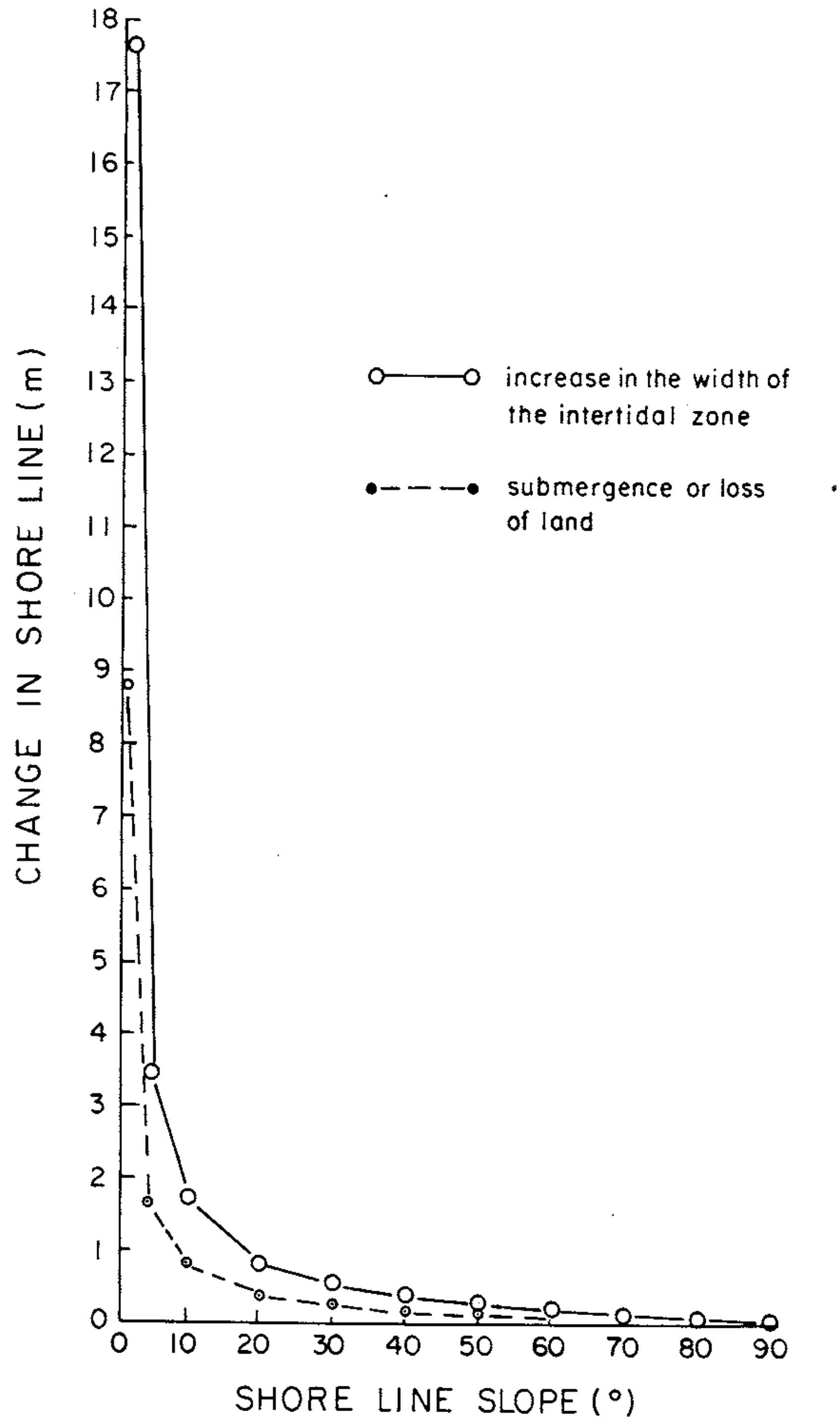

Fig. 4. The influence of shoreline slope and a predicted 30 cm increase in tidal range on the creation of intertidal area and the loss of land.

to an even greater degree. These figures are only to illustrate the importance of shoreline slope on intertidal areas. In nature, many shorelines are irregular and possess steps or regions where slopes vary considerably. Slopes near mean high water (MHW) or mean low water (MLW) will be of great significance in the delineation of new intertidal boundaries. Detailed shoreline profiles are required to predict the precise shoreline changes in a given area.

Salt marshes will also undergo significant increases in area. Nixon (1982) reports that the ratio of high marsh (*Spartina patens*, *Distichlis* and *Juncus*) to low marsh (*Spartina alterniflora*) is approximately 11:1 in Maine. This suggests that the upper marsh area vastly exceeds the low marsh area and will be the salt marsh region which will undergo the most drastic change as low marsh takes over lower high marsh areas and upper high marsh boundaries are extended landward.

Restructuring of biological communities

A change in tidal regime will produce some significant changes in the distribution of intertidal organisms. In the intertidal area, plants and animals are often distributed in vertical zones or layers with respect to tidal inundation, due in large part to their requirements or tolerance for exposure to air and associated stresses (Larsen and Doggett, 1981). The vertical zonation patterns of plants and animals will be altered in several general ways. Firstly, there will be a widening of each vertical band of biota. Where shore slopes are uniform, a 10% increase in tidal amplitude will yield zones that are 10% wider. Many of these zones, however, will also be vertically displaced. Only zones of intertidal biota that inhabit areas at mean water (MW) in the middle of the intertidal zone would not be affected. In the region above MW,

biological zones will be displaced up to 10% upwards from MW. Zones of biota which are below MW will be displaced up to 10% downward from MW.

The transition between upper and lower salt marsh areas occurs as a result of tidal inundation patterns, where upper or high salt marsh areas are infrequently flooded and low salt marsh areas are regularly flooded. The transition zone occurs in the vicinity of MHW. The position of this transition zone, coupled with the great horizontal expanse of high marsh makes this upper marsh region highly susceptible to the influence of an increase in MHW. A potentially considerable, undetermined amount, of area now occupied by high marsh would be expected to be colonized by low marsh from the seaward end of the marsh depending upon the relative slope of the marsh. Near terrestrial borders, high marsh areas will be extended into regions now occupied by upper border plants.

Before a new equilibrium is reached between tide level and high salt marsh regions, more higher marsh will be regularly flooded which may interfere with the activities of some shorebirds. Daiber (1977) found that zones of vegetation, tide level, and salinity factors were related to bird distribution. As discussed by Nixon (1982), "few if any birds are confined to the high marsh habitat." Still, many birds conduct important activities within high marsh areas. Those activities include those of using such areas for cover, nesting, rearing of young, and feeding. Shorebirds that feed on mudflat fauna could benefit from the larger intertidal area as more prey organisms will be available to them.

A pronounced division of biological populations also occurs near the border between the low intertidal and the subtidal. The predicted

10% change in tidal amplitude will result in a lower extension of intertidal communities which will replace organisms of the upper subtidal. This is not considered a significant impact.

b. Restructuring of biological communities

When considering the restructuring of biological communities, it is important to distinguish between the short-term and long-term effects. Under natural conditions, rises in sea level are gradually accommodated by subtle changes in sediment accumulations and distributions, and the slow upward movement of biological zones. The relatively rapid change in tidal range created by the Bay of Fundy project may, however, not provide sufficient time for normal sedimentary processes to occur. In the short-term, biological populations will be displaced due to tidal influence. Where habitat already exists for recolonization, such as on rocky shores, a new equilibrium may be quickly reestablished between the new tidal regime and biological communities. In other regions, such as high salt marshes, a considerable period may be required to allow normal sedimentary processes to elevate marsh soil heights to the levels which will again support high marsh and hence the biological system will be disrupted for several years.

c. Increased area for ice formation

The formation of sea ice in the intertidal is a function of air and water temperatures, salinities, currents, and water depth. An increase in tidal range will result in a larger area with shallow water that can cool and freeze faster.

Given the variation in mudflat and marsh intertidal slopes, we might expect between 5 and 10% increase in intertidal area available for new (additional) ice formation.

A rooted ice mass at the upper edge of the intertidal. Following the tidal range increase, the rooted ice mass or "ice foot" should actually protect the newly inundated salt marsh edge from erosion by waves, however, in spring during ice breakup, there would be considerable erosion as blocks of *Spartina* peat are ripped up and rafted seaward (Thompson, 1977; Newbury and McCullough, 1982). Some deposition, however, will also occur, when the ice/*Spartina* blocks drift landward on high spring tides, become stranded and leave behind incorporated peat and sediment (Gordon and Desplanque, 1983). However, it is anticipated that erosion will exceed deposition.

Since the ice erosion process will predominantly involve marsh, there should be little initial effect on the marine benthos in the higher ice foot zone. The ice erosion will hasten the natural wave erosion process expected with the increased tidal range, and shoreline readjustment will take place faster where ice formation is strongest.

Although the increased range of the tide will also increase the exposure of lower intertidal mudflat, the effects of sea ice in this region may be less dramatic. We would expect, however, an increase in the area covered by frozen mud crust in the expanded intertidal (seaward of the ice foot). Some investigators feel that the frozen mud inhibits sediment resuspension during the coldest periods (Knight and Dalrymple, 1976) resulting in lower quantities of particulate matter in suspension during the winter months. However, the expansion of the frozen mud crust could be detrimental to some marine organisms.

In summary, increased ice formation may be expected to occur in overlying waters due to the temporary increase of exposed intertidal area. The upper intertidal sediments and marsh will be encased by sea ice at the highest levels of the increased tidal range, while lower intertidal will experience an expanded frozen mud crust. With ice breakup in the spring, large blocks of upper intertidal marsh will be lifted, and transported both seaward and landward in the estuary. This erosion will take place rapidly as the shore attempts to stabilize relative to the new tidal range. The quantitative significance of these events is, however, unknown.

d. Increased tidal prism of estuaries

The tidal prism is the volume an embayment between mean low tide and mean high tide. The size of the tidal prism of an estuary is one of the factors which controls the mixing or exchange of the estuarine water with open sea water. For this reason, the size of the tidal prism also affects the salinity and the flushing rate of the estuary, and the dampening of temperature extremes in summer and winter. It will be convenient for our discussion to divide the estuaries of Maine into two groups, large, wide-mouth systems which may be thought of as "arms of the sea," and small systems which open to the sea through tidal inlets.

For larger estuaries, a simple "exchange ratio," r, for any section of an estuary is given by the ratio of the tidal prism, P, of that section to the sum of the tidal prism and the volume of the section at low tide, V, i.e.,

$$r = \frac{P}{P + V}$$ (See, for example, Dyer, 1973).

For an idealized estuary with a rectangular cross-section,

$$r = \frac{R}{R + V/\text{area of section}} \quad \text{where R is the tidal range.}$$

Let us consider first the lower reaches of the estuary, in which the low water volume is nearly constant through time. If we let Δr be the change in the exchange ratio which results from a given change in tidal range, ΔR, we find simply, to the first approximation,

$$\frac{\Delta r}{r} = \frac{\Delta R}{R}.$$

Now we apply this relationship to the lower reaches of an estuary in the Boothbay Harbor area, where the mean tidal range is 8.8 ft. If the mean tidal range is increased by 1.0 ft, we have

$$\frac{\Delta r}{r} = \frac{1.0}{8.8} = 0.11 \text{ or an increase in the exchange ratio of 11\%.}$$

By way of comparison, the mean spring tide range at Boothbay Harbor is 10.1 ft, ΔR is 1.3 ft, and

$$\frac{\Delta r}{r} = \frac{1.3}{8.8} = 15\%.$$

That is to say, the increase in the exchange ratio which occurs now at mean spring tide is 1.4 times the increase which will occur as a result of barrage construction in Minas Basin.

In summary, construction may cause an increase in the exchange ratio in the lower reaches of Maine estuaries on the order of 10% or more. As the fresh water inflow is relatively small, and there is little differential between the salinities of the seawater and the resident water of lower estuaries, such alterations of exchange should not alter significantly salinity regimes.

In the upper reaches of large estuaries the tidal range is considerably reduced from its value along the open coast. Assuming that the effect of barrage construction would be to increase the tidal range by the same proportion as it increased in the lower reaches of the estuary, the exchange ratio due to tidal action would be increased by approximately 10% as in the lower reaches. However, in upper estuaries, the variability of salinity and flushing depend much more upon changes in the fresh water input than on tidal fluctuations.

One caveat should be noted. Merrymeeting Bay is a large tidal freshwater wetland at the confluence of the Kennebec and Androscoggin Rivers. At present, brackish water is found at the bottom of the Bay only at the dry times of the year (Larsen and Doggett, 1979), and hence it does not come into contact with the aquatic vegetation which supports the rich wildlife resources of the area. A slight increase of salt intrusion into Merrymeeting Bay, as suggested by the last paragraph, may be sufficient to disrupt the salt intolerant vegetation presently dominating, and hence change the entire ecological balance. In summary, a small physical change may have a large biological effect if it occurs at a sensitive point. Additional fieldwork is needed to identify these sensitive areas.

Next small estuaries with tidal inlets are examined. Again, we consider the change in the value of the exchange ratio which would result from a 30 cm increase in tidal range. In this case, however, we can no longer consider the system to have a rectangular cross-section. Tidal inlets and basins widen with increased elevation and, therefore, provide increased access at higher stages of the tide. For this reason, the additional tidal elevation at high water would increase the tidal

prism by more than its proportion of the total range. On the other hand, at low water, tidal inlets and channels are very resistant to flow and often the estuary basin has accumulated sediment to the extent that little water remains within it at present low tide levels. For these reasons, the decreased tidal elevation at low water would increase the tidal prism by less than its proportion of the total range. Thus, these two effects, the one at high tide and the other at low, work against each other, and we will consider that they cancel one another. This leaves us, once again, with an estimated increase of 5 to 10% in the exchange ratio due to the increased tidal prism. With an expanded tidal prism, summer water temperatures would be decreased somewhat, and winter temperatures similarly increased as the result of increased exchange with the more thermally moderate seawater.

With an increase in the flushing rate, those estuarine pollutants that are in suspension or solution will be mixed with "cleaner" marine water at a higher rate. This could have a positive benefit to the estuary, in that it would tend to purge itself more rapidly following pollution input.

The turbidity of the estuary is primarily caused by organic and inorganic particulate matter in suspension. The most common sources of particulate inorganic sediments are rivers, coastal erosion and resuspension from the tidal flats and channels (Biggs, 1970). In contrast, the organic matter sources include phytoplankton, resuspended intertidal microalgae (Baille and Welsh, 1980), detritus from salt marshes and, of course, man's sewage effluent. In considering flushing rates alone, the turbidity values will decrease more rapidly after a "turbidity event" under proposed higher tidal ranges. In fact, the overall sedimentation

rate of the estuary could be slightly reduced by increased flushing of the particulates seaward.

As an example of the possible changes that could occur in one estuary, consider Great Bay, New Hampshire. We have calculated that the total tidal prism is 18.7×10^6 m^3. All this water must flush out of the system in approximately 6 hours, with an average discharge of approximately 813 m^3/sec. Since it must flow through a narrow channel, we can measure its cross-sectional area and determine the average velocity (0.21 m/sec).

Now assume we increased the tidal range by 30 cm. This will increase the tidal prism to 21.2×10^6 m^3. This will increase the average discharge 921 m^3/sec, and the mean current to 0.24 m/sec, about 13% faster than before.

Estuarine flushing models presently exist for selected northern New England estuaries (C. Garside, pers. comm.). These models could provide numerical estimates of changes at moderate cost.

e. Effects on groundwater hydrology

The following examination of groundwater hydrology was prepared by A.L. Tolman, a hydrogeologist with the Maine Geological Survey.

In the classic case of a homogeneous, isotropic aquifer, such as a large sand island, bordering a salt water body, the relationship between the fresh water and salt water is well-defined. The relationship is governed by the difference in density between salt and fresh water and by the net flow of fresh water towards the salt water body.

Although these basic principals hold true for more complex geologic and hydrologic systems, such as those which exist along the Maine coast,

their application to these systems is not simple. For a static, homogeneous system, the relationship predicts that for every foot of elevation of the fresh water over the salt water level (sea level), there will be forty feet of fresh water on top of the underlying salt water wedge. This thickness will adjust nearly instantaneously to any increase or decrease in the relative elevations. Thus, the depth of fresh water under a given point on the land will thicken and thin with the tides. At most places near the coast, the fresh water wedge is many hundreds of feet thick and this displacement does not impact wells. However, several complicating factors cause salt water to degrade water quality at a number of areas along the coast.

The major complications in the ideal picture are:

1) Ground water flows towards the ocean at varying rates and volumes.

2) Aquifer permeability and degree of connection with the ocean varies widely and is governed by fracture density, spacing, and orientation.

3) Pumping from wells reduces the fresh water head and causes local "upconing" of salt water.

4) Fresh and salt water intermix to form a brackish zone which is less well defined than the ideal boundary.

These complications make it difficult or impossible to predict the number of wells which might be affected by a change in tidal fluctuations. However, some estimation of areas already affected is possible. In these areas, it can confidently be predicted that increases in high tides will further worsen the situation.

In much of the populous southern coast, the near-shore aquifer has already been abandoned because of pollution and/or inadequate yield and public water supplies are in place. However, in the less densely populated, emergent (rocky) portions of the coast, private wells remain the primary source of water for year-round residents.

Should tidal fluctuations increase, the salt water wedge would rise higher at each high tide and, at a minimum, those areas already experiencing salt water intrusion problems would find their problems more severe. If this effect is coupled with the current increase in year-round development along the coast, it is likely that the number of towns affected will increase.

f. Sediment translocation within the intertidal zone

The northeastern estuarine intertidal is in a delicate state of balance between sediment erosion and deposition. Studies by Anderson et al. (1981) have shown that periods of intertidal erosion and deposition occur over the year as well as at the same time on a given tidal flat. The sequence of events seems to be slow, sediment accumulation punctuated by episodic erosion by storm waves, rainfall and ice.

Two of the major physical processes, waves and tidal currents, both decrease in intensity with increasing distance from shore (Reineck, 1967). In estuaries the consequence of this decreasing energy gradient is a somewhat coarser grain size at the lower intertidal levels "fining" upward toward the high tide line.

What then would be the effect of a small increase in the tidal range on this somewhat unstable environment? One effect would be an increase in both wave and current shear stress acting on any given depth

zone in the intertidal. Some investigators think wave stress is the more important factor in intertidal resuspension (Anderson, 1972). A critical stress, induced by waves, is necessary to put the bottom sediment into suspension. This critical shear is a function of the bottom sediment characteristics, as well as the physical properties of the wave. The shear stress is proportional to the wave height, wave period, and most important - the depth of the water. One can calculate the wave induced shear stress from the formula.

$$T_o = \mu \left(\frac{\pi}{Tv}\right)^{\frac{1}{2}} \cdot \frac{H\pi}{T \cdot \sinh \frac{2\pi D}{L}} \quad \text{(Jackson, 1973).}$$

Where μ = viscosity

v = kinematic viscosity

T = period

H = wave height

D = depth of water.

By increasing the tidal range, and maintaining the same wave characteristics we subject the lower intertidal to increased shear (shallower water). The net consequence will be increased erosion in the newly-formed, lower-intertidal and subtidal zones. We would expect the bottom sediment to rapidly adjust to the new forces and correspondently "coarsen up" in the winnowing process.

If we assume that an increase in the tidal range increases the width of the intertidal area, we might expect a larger decrease in wave energy across the tidal flat. Anderson (1976) has shown that the energy in small amplitude intertidal waves is proportional to distance over which the waves travel. That is, there is a severe loss of energy as a wave train passes the intertidal from deep to shallow water. If the

intertidal zone expands we can expect a decrease in the wave energy arriving at the upper intertidal and hence finer sediments in that area.

In summary, after equilibrium is reached, an increased tidal range should increase wave "winnowing" at the lower end of the newly exposed intertidal, while wave action should be reduced at the upper end. However, these general observations must be tempered with events taking place in the supratidal (next section).

g. Sediment translocation within the supratidal zone

The supratidal can be defined as that area above high-high tide that is occasionally inundated by extreme spring tides and/or storm tides. In estuarine systems, high marsh areas are often dominated by the grasses *Spartina*, *Juncus* and *Distichlis*.

In New England, the upper intertidal often is not a smooth grade into a salt marsh environment, but instead is characterized by an erosional "step" going from fine-grained sediments to peaty, salt marsh sediments. This step may in part reflect historically rising sea levels and continued landward erosion (Brunn, 1962). With a rapid increase in tidal range, however, we can expect this "step" boundary to erode landward. As erosion proceeds, the organic rich peat sediments will be eroded from the "step" front and carried both out into the intertidal zone and estuary, as well as flooded landward onto the new "supratidal."

Erosion will be especially rapid during high spring tides, particularly in the early spring immediately following ice-out. Depending on the texture of the salt marsh sediments, we would expect a new equilibrium to be reached within a short time (2-3 year period) (Newbury and McCullough, 1982). Although the salt marsh area will be temporarily

diminished, the new upper intertidal mudflat area will be made available for colonization by other benthic organisms. Although some of the peaty debris will eventually end up in the sediments, this organic matter will have little nutritional value for the invertebrate animals already in place. The net result will be a landward expansion of the supratidal zone accompanied by seaward erosion of the Spartina marsh. The estuarine waters will be temporarily enriched in organic peaty debris until erosion stabilizes and equilibrium is reached.

h. Inlet stability

Many tidal inlets are permanent and seem to change very little with time, while others open and close as a function of natural processes. Much of the work on the stability of tidal inlets has concentrated on examining the empirical relationship between the cross-sectional area of the inlet and the tidal prism of the bay landward of the inlet (Escoffier, 1977). Probably the most quoted investigator in this study area is O'Brian (1931, 1966) who developed a model relating inlet size and tidal prism following the formula:

$$A_c = b\Omega^n.$$

Where A_c is the cross-sectional area of the tidal inlet below mean sea level, and Ω is the tidal prism during the spring tidal range of the tide. The empirical constants b and n are related to whether the inlet has been "fixed" by jetties or is in the natural state. Since O'Brian's early investigations there has been a great deal of additional work refining the empirical equations for each coast (Jarrett, 1976).

Regardless of which empirical equation is used, an increase in the tidal range results in an increase in the cross-sectional area of the

inlet. If the inlet is natural (unfixed by jetties) we would expect erosion to take place on either side of the inlet until a new equilibrium would be reached. On the other hand, if the inlet sides are fixed by jetties, then the channel would have to deepen to respond to the governing empirical relationship.

Another significant problem with increasing the tidal range and inlet stability is the interception of littoral sand drift by the inlet during the normal ebb and flood process. Although most sediment by-passes the inlet in the longshore current, a small amount always enters the inlet on the flood tide and exits on the ebb. This sediment can be temporarily stored and incorporated into ebb and flood tidal deltas often found on either side of the tidal inlet (Dean and Walton, 1975). At this point we are not sure what an increase in tidal range would have on the movement of sediment into or out of the inlet. We would expect, however, the ebb and flood tidal deltas would change both size and shape until a new equilibrium was reached.

If the tidal inlet is fixed (with jetties) and deepening is the consequence of increasing the tidal prism, we might expect increased wave action further in the back bay area, as the waves will be less dampened out in the inlet passage. This would temporarily cause some local bay side erosion, perhaps making the harbor interiors somewhat "rougher" as mooring sites.

2. CONSEQUENCES OF HIGHER HIGH TIDES

We have assumed for the purposes of this study that Fundy tidal power development would cause a 30 cm or 10% increase in tidal range along the coast of Maine, and that this increase would be equally

divided between higher high tides and lower low tides. In considering higher high tides, we first discuss their role in producing shoreline retreat. There are two ways in which this could occur. First, there is the direct increased flooding frequency of the coastal fringe of the terrestrial environment (this has been discussed, in part, above), and second, higher high tides would raise the elevation of storm wave attack on the shoreline, and thereby increase the rate of coastal erosion. We will discuss these two effects separately.

a. Landward movement of high tide line/submergence

The terrestrial and marine environments are separated by the intertidal zone. There is no established level within the intertidal zone which is universally accepted as marking the seaward limit of the terrestrial environment. Two candidates would be the mean spring high tide line and the mean annual high tide line. However, regardless of the specific level chosen, our task is to determine the total area which lies between the present position of that line and the position that the line would occupy if it were 15 cm higher than its present level.

Our approach to this task was to first determine the distribution of the land surface area of the State of Maine with respect to its elevation above sea level. This distribution may be presented in the form of a cumulative frequency curve which presents the percentage of the area which is higher than any given elevation. Such a cumulative frequency curve is referred to as a hypsometric curve. Next, we draw a tangent to the hypsometric curve at the point that it crosses sea level (zero feet elevation). From the slope of the tangent line can be

determined the amount of land area which lies between sea level and any higher elevation near sea level.

We developed a hypsometric curve for the State of Maine by sampling elevations at 61 points using a grid applied to the USGS 1 to 500,000 scale topographic map of the state which has a contour interval of 200 ft. The curve produced from these data is shown in Fig. 5. The tangent to the curve at sea level has a slope of 1 foot of elevation for each 0.042% of surface area, or 0.5 ft (approximately 15 cm) for each 0.021%. Taking the surface area of Maine, exclusive of inland water, to be 31,000 square miles, we find that 0.021% of this area represents 6.5 square miles. This, then, is an estimate of the area which would be submerged by a high tide level increase of 15 cm. It is equivalent to 17 km^2 (4,200 acres) or a mean strip of land 2.5 m wide. This area would be made up of lowland regions above present MHW bordering Maine's 6,705 km coastline (Topinka and Korjeff, 1981).

The previous value of 4200 acres may well underestimate the extent of coastal inundation in that the hypsometric curve used for its calculation has incorporated all the elevations in the State of Maine rather than those of coastal lowlands. Independent estimates of coastal drowning suggest that more than 10,000 acres may be inundated (J. Kelley, Maine Geological Survey, pers. comm.). While more precise measures of anticipated coastal inundation are needed, both estimates suggest significant coastal drowning. Inundation along southwestern coastal areas may be relatively more severe due to its more gentle coastal slope. The high abundance of salt marsh is typified by its mean coastal vertical relief of 24 ft over 400 m adjacent to the sea. This

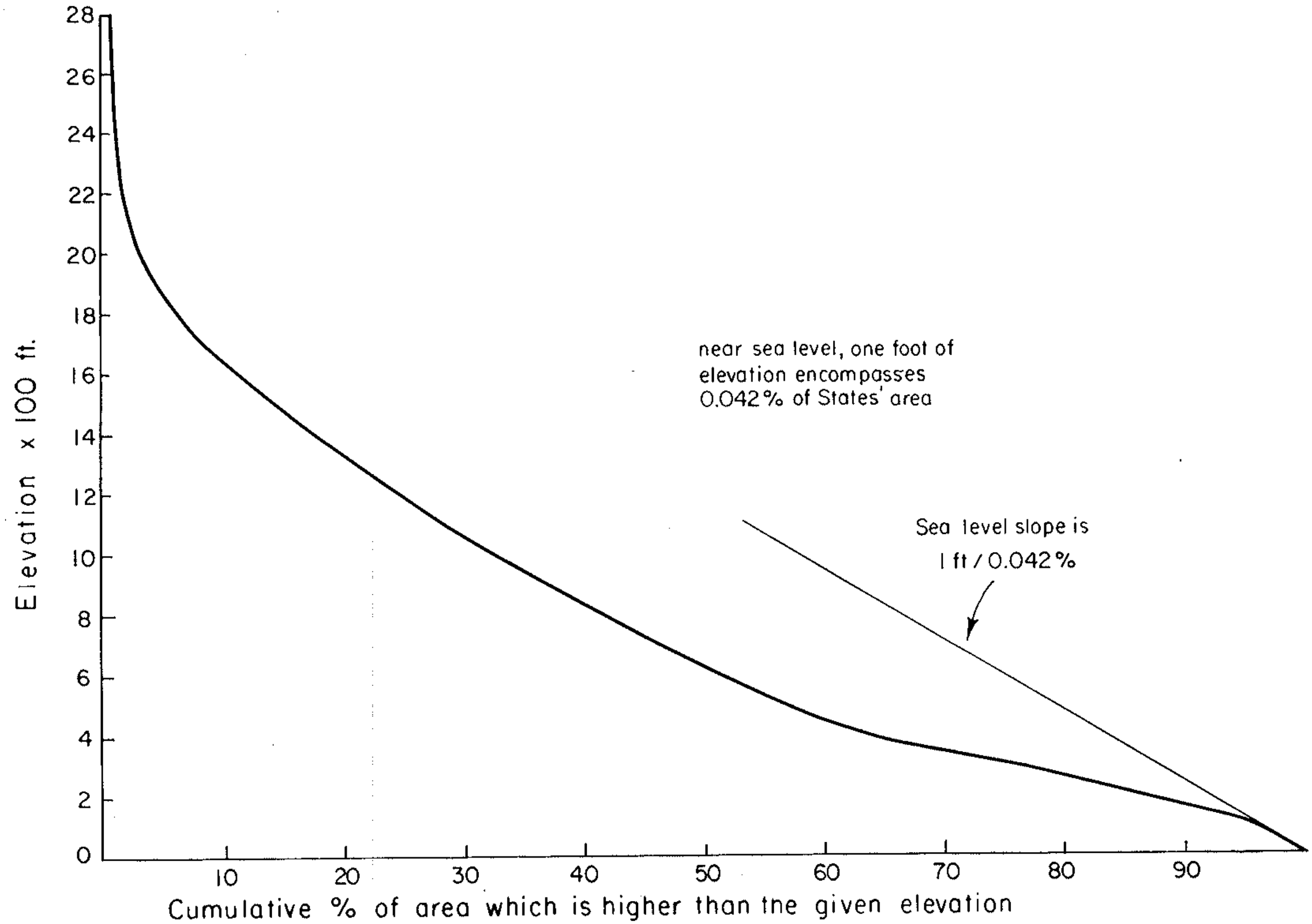

Fig. 5. Hypsometric curve for the State of Maine.

is great compared to reliefs of 62, 69 and 55 ft for northcentral, northeast and southcentral coastal areas, respectively (J. Kelley, pers. comm.).

b. Landward movement of beach profiles/erosion

Beaches are formed by the action of waves on deposits of loose sediment. Beach form adjusts to the characteristics of both the waves which deliver energy to it and the tides which determine the elevation of the energy input. Generally speaking, other factors being equal, the higher the tide level, the greater the rate of energy input to the beach. Since the low tide effects are small compared to those at high tide, we will ignore them for this first approximation, and consider that the primary effects will be due to increasing by 15 cm the level of maximum energy input. In short, while we understand the limitations of this approach, we will imagine the beach response to be that which would accompany a 15 cm rise in sea level. In so doing, we follow the example of M.L. Schwartz (1967), who tested Per Bruun's (1962) theory of sea level rise as a cause of beach erosion by measuring the variation of beach profiles between neap and spring tide.

Bruun (1962) presented an expression for the determination of the beach retreat which would result from a small rise in mean sea level. It is based on the assumption that the beach profile would remain unchanged in form, but would be shifted upward and landward. Since his original study, Bruun's method has been applied in a variety of forms by many investigators of beach processes (Schwartz, 1965, 1967; Dubois, 1975, 1976, 1977; Rosen, 1978; Hands, 1979; Weggel, 1979). Allison (1980) presented a rigorous derivation of the relationship between sea

level rise and beach recession, from which he concluded that for most cases Bruun's expression "gives high accuracy" in the form

$$s = \frac{a\,l}{h}$$

in which s is the shoreward displacement of the beach profile, a is sea level rise, l is the length of the equilibrium profile and h is the profile height, being the sum of the mean water depth at distance l from the shore and the shore elevation above mean sea level.

In attempting to apply this expression to Old Orchard Beach we immediately find the problem common to all such attempts: finding the offshore limit of the profile. Bruun (1980) suggests a depth range of 15 to 21 m for the offshore limit "on a long term basis" for exposed shores. We made an estimate of the depth of the offshore limit using the method outlined by Weggel (1979) and the shore profile at Old Orchard Beach given by Emery and Uchupi (1972, p. 19), from which we derived a value of 13 m. For the purpose of calculating the shoreward displacement of the profile we will use 15 m as the depth of the offshore limit of the profile, which corresponds to a distance of 2,200 m from shore (NOS chart 13286). Combining these with the corresponding values for the onshore portion of the profile, we arrive at values of 2,280 m for profile length and 17.4 m for profile height. Assuming a "sea level rise" of 0.15 m, we arrive at an estimated profile retreat of 20 m.

Summarizing, we have applied Bruun's method of estimating shore profile retreat to the present problem. The projected tidal range increase of 30 cm would be accompanied by no change in mean sea level. However, it would increase the elevation of wave energy input to beaches, and therefore we have assumed that in its effect on beaches, it

would be equivalent to a 15 cm rise in sea level for this preliminary calculation. Applying Bruun's method to a sample beach (Old Orchard Beach) we estimate a resulting long term retreat of 20 m. This potential beach erosion may also be offset to some extent by lower low tides and increased bluff erosion which may add sand to beaches (J. Kelley, pers. comm.).

It is important to realize that beach changes would take place over many years and would result, not in a great change at any one time, but as a long term (perhaps 50 year) increase in the net rate of beach erosion. Beach berm and backshore elevation would be insignificantly increased by approximately 15 cm.

c. Increased penetration of storm tides and coastal flooding

Coastal storms and hurricanes cause storm tides which, historically, have ranged from 6.8 to 9.1 feet above the mean tide level. The extensive damage caused by the February 1978 northeast storm generated federal agency interest in analyzing historical coastal storm data (Stone and Webster, 1978) which is very useful in analyzing the effects of a 30 cm tidal range increase on future coastal storm impacts along the Maine coast.

Stone and Webster (1978) and the U.S. Army Corps of Engineers (1979) have developed predictive curves for coastal storm tides at Portland (Fig. 6) using the Pearson Type III curve of expected probability of coastal surge levels. Completion of the Fundy tidal project will alter the exceedence probability of storm tide elevations, i.e. the water levels observed during storms.

Coastal storms induce flooding of low-lying areas, wave erosion of coastal banks, beaches and sand dunes and create overwash conditions behind beaches. Beaches and banks are in dynamic equilibrium with lower energy storms, but not with higher-magnitude storms. In terms of analyzing unexpected storm damage, all storms in the past 40 years were analyzed for their storm tide levels in relation to the amount of <u>unexpected</u> damage to man-made structures, roads and utilities. A cursory examination of these storms indicates there is a division between storms with an exceedence probability below 13.3% (those storms with a higher exceedence probability cause little or no expected damage, those with a lower exceedence probability cause unexpected damage). This exceedence probability of 13.3% corresponds to a coastal water level of 7.9' above mean tide level.

Between 1940 and 1979, eleven coastal storms or hurricanes occurred with coastal storm tide equalling or exceeding the 7.9' elevation. These storms included the storms of 1978, 1976, 1972, 1963, 1958 and 1957, Hurricane Carol in 1954 and the storms of 1945 and 1944.

If 15 cm of tidal amplitude were added to coastal storm tide levels, then a coastal storm of exceedence probability of 45% (water level of 7.4 feet above mean tide level) will become a storm tide of exceedence probability 13.3% (water level of 7.9 feet above mean tide level). Historically, 30 coastal storms which would have affected the Maine coast over the last 40 years had the tidal amplitude been 15 cm higher, would have been approximately 2.5 times greater in number.

The Fundy project would not increase the number of storms. It could increase the frequency of "damaging" storms by 2.5 times. Moreover, the magnitude of storm damage expectancy will increase. With

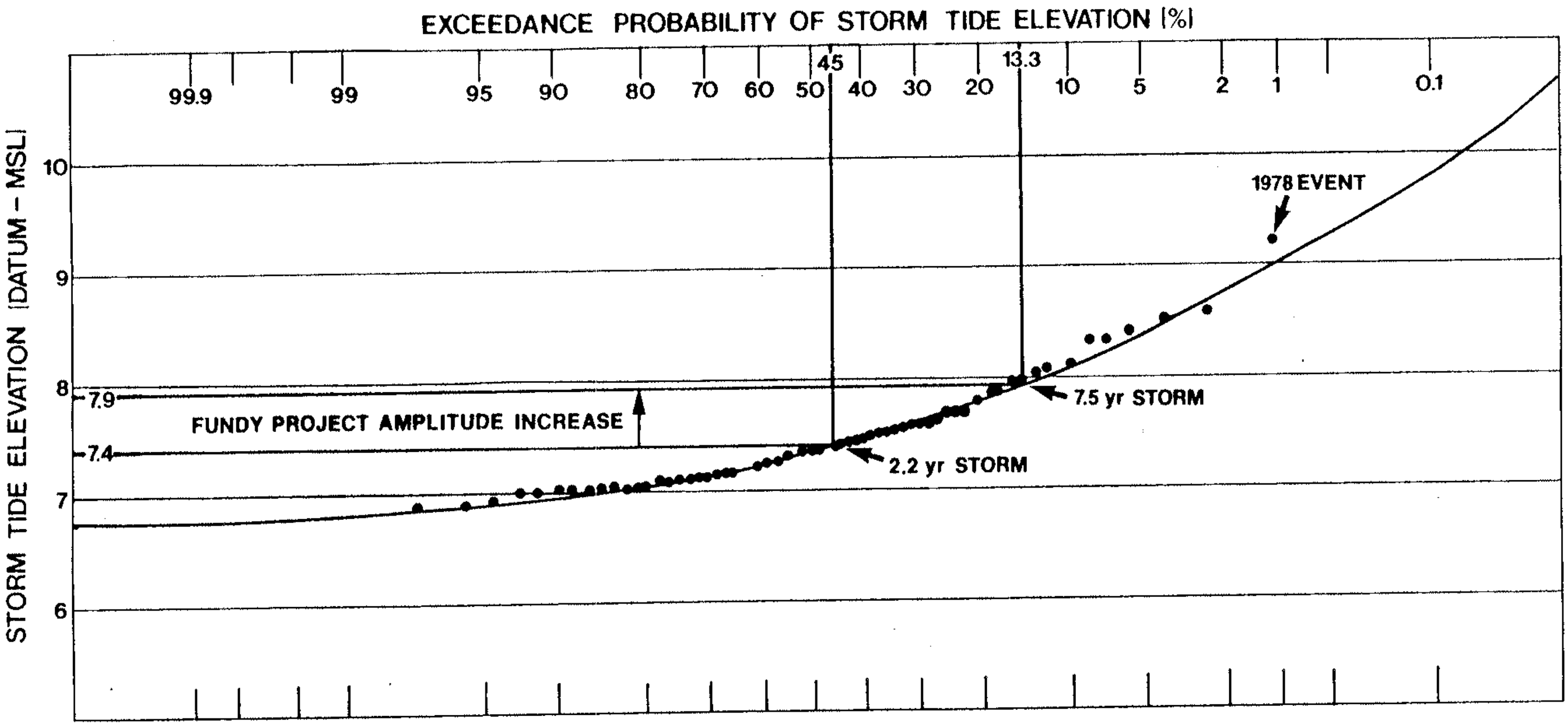

Figure 6: Influence of the Fundy Project Tidal Amplitude Increase on the Exceedence Probability of Storm Tide Elevations

an increase of tidal amplitude of 15 cm, a 100-year storm rise in sea level will become a 300-year storm rise in sea level; a 50-year storm - a 200-year storm; a 10-year storm - a 25-year storm; a 7.5-year storm - a 20-year storm; and a 2.2-year storm - a 7.5-year storm. Those changes are defined by changes in the coastal storm tide level. For the purpose of our preliminart calculations, it is assumed that the storm is coincident with high tide, a situation which may, but does not always occur. The frequency and magnitude of high water levels associated with damaging coastal storms will increase as a result of the Fundy project.

This increase in high water levels associated with damaging storm frequency and magnitude could have a dramatic effect on coastal beaches - beach retreat rates could increase over the 5-year construction period of the tidal project and would continue until a new average retreat rate is established - this should be established relatively shortly after the completion of the project - within 5 to 10 years.

1) Flooding of low-lying areas

Presently, the Federal Emergency Management Agency is preparing detailed maps for coastal Maine indicating the extent of coastal flooding to be expected during the 100-year and 500-year floods in regions near high water elevations.

Flooding of low-lying areas due to the increase in daily tide amplitude will not increase the area of flooding dramatically. The extent of coastal flooding of low-lying areas due to large magnitude coastal storms can be determined by reference to those maps as being less than what will occur during the 500-year storm.

The impact of flooding will be felt more frequently than previously. The most dramatic effect which the Fundy project will have on the upland and supra-tidal areas will be the effects on coastal storm tides and erosion and damage created by coastal storms. While we can predict the theoretical increase in frequency and magnitude which the project will have on coastal storm tides, the resulting rate of erosion on coastal beaches and banks cannot be accurately predicted without further analysis of available information. An in-depth analysis of historical storm effects on beach erosion and coastal bank retreat at specific localities is required to predict probable rates of erosion.

3. CONSEQUENCES OF LOWER LOW TIDES

a. Seaward movement of low tide line and loss of subtidal habitat

Typically, the lower portion of the intertidal zone decreases in slope as it approaches the subtidal nearshore bottom. Such features as sand bars on exposed shores and mudflats in protected waters characterize this zone. Because of their low slope, a significant increase in the exposed areas of these features would result from a lowering of the mean low tide level by 15 cm. If we approximate the bottom slope of the intertidal-subtidal boundary as 0.01, we find that a zone 15 m wide of presently submerged bottom would be exposed at low tide.

Along dominant rocky shores where shore slope is in the vicinity of 11° (Topinka et al., 1981), a 15 cm depression of MLW would produce a loss of subtidal habitat of approximately 0.8 m, which would then be occupied by intertidal organisms. Presuming that suitable habitat was available, however, all nearshore subtidal zones would eventually shift downward with no significant loss of subtidal habitat or associated biological populations.

B. TIDAL CURRENT CHANGES

1. HORIZONTAL FLUXES

a. Effects of increased current on ice formation, accumulation and transport

The proposed increase in tidal range will initially increase the amount of shallow, intertidal area that is conducive to ice formation during periods of high water (see above). However, the same increase in tidal range will slightly increase the tidal currents which should, in part, inhibit ice formation in the channel regions (Gordon and Desplanque, 1983).

As tidal currents increase, the more well-mixed water, especially in the estuary, will be more difficult to freeze. This will mean that channels will remain open for a longer period of time, and some areas that formerly were closed because of ice formation will be more open, or will have the "ice-free" season extended. For the most part, these changes could be economically beneficial.

However, the increased current affects not only the formation of the ice, but also ice transport. With increased current one could expect the "ice-out" period to be shortened. Again, for the most part this would be beneficial and add to the usable days of a given harbor or specified pier. However, increased currents would move drifting ice blocks with slightly greater force into boats and piers. Areas that formerly experienced a prolonged, "gentle" decay of intertidal ice would now see severe ice movements, perhaps with ice piling up in restricted flow regions.

b. Reduced retention of larvae and sexual products

Greater rates of estuarine flushing as discussed in the section Increased tidal prism of estuaries, will act to disperse planktonic organisms and their gametes including larvae of clams, mussels and commercial worms. As a result, retention of these organisms in estuaries will decrease, lessening the likelihood that those products will again seed the same portion of a given estuary. Increased dispersal of these products may, however, permit colonization of other areas in more remote estuarine areas. This might be of some advantage if depleted shellfish beds were exposed to greater levels of colonization from more remote regions. At the same time, some intertidal organisms may suffer an increased loss of planktonic stages to offshore areas which will not support those organisms.

c. Development and spreading of red tide blooms

Although it is not possible to make firm predictions with regard to possible tidally induced changes in red tide levels, it is possible to speculate on some potential influences on red tide growth and distribution. Mixing processes, particularly the formation of tidal fronts between well mixed and stratified waters, often produce accelerated growth of phytoplankton particularly dinoflagellates, including red tide organisms (Seliger et al., 1979). This led Reid (1980) to suggest that altered tidal regimes and circulation patterns, induced by tidal power construction in the Bay of Fundy (Gordon and Longhurst, 1979), may change patterns of paralytic shellfish poisoning in the Gulf of Maine. Stronger bottom currents induced by an increased tidal amplitude may also increase the occurrence of red tide blooms.

Red tide cysts are widely dispersed over the Gulf of Maine (Lewis et al., 1979) where they may initiate red tide blooms (Anderson and Wall, 1978). Red tide cysts resting on the bottom will have a greater likelihood of being transported to other bottom areas and into surface waters where they may excyst and begin to grow. In shallow waters, wind mixing may stir cysts into the water column; tidal mixing could be more important in deeper waters.

Once in the water column, red tide organisms may spread over larger regions more quickly due to increased tidal velocities. Increased mixing of nutrients into surface waters (refer to p. 77) would also be expected to enhance the growth potential for red tide. An increase in bottom current velocity will also bring additional red tide cysts into the water column where the cysts may be directly consumed by organisms such as clams or mussels. Both motile cells and cysts of Gonyaulax may be ingested by shellfish (Yentsch and Mague, 1979) with cysts having greater toxicity per cell (Dale et al., 1978). As a result, those organisms would accumulate more red tide toxin even during periods when red tide blooms do not occur.

At this point, it is difficult to estimate the degree to which red tide contamination of shellfish would be changed as a result of a 10% increase in tidal range. Although it is possible that red tide contamination could increase, the complexity of red tide contamination processes makes this situation difficult to evaluate.

d. Restructuring of biological communities

As discussed earlier, an increase in tidal current of 10% could influence the patterns of intertidal sediment distribution and hence the

resident plant and animal communities. In the subtidal, sediments would also be rearranged with the greatest impacts being demonstrated in those areas exhibiting the greatest change in current activity. Eventually, the sedimentary regime and associated biota will come into equilibrium with new current patterns. During this transition period, biological populations will experience a stress as some sedimentary habitats are reorganized. For some habitats such as salt marshes, the transition period could extend for many years.

2. VERTICAL FLUXES

a. Increased mixing depths of surface waters

The extent of vertical mixing that is induced by tidal action is described in a model developed by Simpson and Hunter (1974). The major component of this model which dictates whether the water column is stratified or mixed is Log H/U^3, where H is the depth of the water and U^3 is the tidal velocity-frictional parameter. This model shows that Georges Bank and Nantucket Shoals are tidally mixed with additional mixing off the Bay of Fundy and Nova Scotia. Although tidal mixing alone does not account for all vertical mixing, satellite imagery has confirmed that much of the mixing is apparently tidally driven (Yentsch and Garfield, 1981). These mixed areas total approximately 30% or 4.2×10^4 km^2 of the total 1.40×10^5 km^2 area of the Gulf of Maine region.

Due to the lack of knowledge concerning the physical mechanisms which control vertical mixing processes, it is not possible to fully quantify all vertical mixing processes. It is, therefore, not possible to translate an increase in tidal range into an absolute alteration of water column structure. It is, however, possible to develop some useful

perspectives on the influence of a higher tidal range on the water column.

The increase in tidally induced current velocity will not be uniform in all areas of the Gulf of Maine. Several factors, such as water depth, heat-bouyancy effects and other parameters will influence the degree and type of mixing which will occur. For example, in deep water, a minor increase in tidal currents would not be sufficient to cause destratification of otherwise stratified surface waters. Similarly, the influence of greater mixing would not be strongly felt in regions that were originally unstratified. The question of how much more of the Gulf of Maine will become better mixed and what will the extent of this mixing be is of great significance but must await further investigation. It is clear, however, that increased vertical mixing of the water column will be accelerated in some areas such as those which presently are affected by the two week spring-neap tidal cycle.

b. Reduced surface water temperature

Greater vertical mixing in summer would bring colder water to the surface. The result would be lower surface water temperature and destratification of the water column. It has, however, been suggested that increased tidal current velocities may act more to result in the increased mixing of bottom waters with a lesser effect on surface mixing (Greenberg, pers. comm.).

The lowering of surface water temperature can be expected to be of greater magnitude in regions in which tidal currents were greater, water depths shallower, surface waters warmer, and water columns highly stratified. Significant lowering of temperature would therefore be

expected only in shallow, stratified waters, during summer and would occur on a local basis due to other physical circumstances. The general effects of lower surface water temperatures in summer are given in the following sections.

c. Altered meteorological conditions

Heat is exchanged between the sea and the atmosphere at the air-sea interface. Normally the air temperature over the sea and in the coastal zone is determined by the water temperature. When the temperatures of the two masses differ significantly, fog or sea smoke results. During the summer, onshore breezes develop as cool air from over the water moves under the heated air over the land mass.

Changing the sea surface temperature, even on a local basis, will have an effect on the atmosphere. Interviews with staff of the National Weather Service (NWS) indicate that, if the projected decreases in summer surface water temperature materialize, corresponding changes can be expected in the atmosphere of the coastal zone. These changes will be manifested as increased fog and stronger onshore breezes. The NWS staff was not able to put a magnitude on these changes but indicated that, with the proper data, it would be technically feasible to make reasonably precise predictions by utilizing an air-sea interaction model.

d. Altered growth and reproduction patterns of biota

Different organisms have different temperature requirements. These requirements may be expressed as temperature tolerances near the extremes of their physiological limits or for survival or some specific

activity such as reproduction. The effects of temperature are also pervasive and influence the physiological performances in many subtle ways. A decrease in water temperature of $1^{\circ}C$ may decrease respiration and many other behavioral activities such as swimming or feeding rates. While respiratory loss will be less, feeding rates may also be lower and for many organisms the direct affect of lower temperature may result in decreased growth rates.

The web of interactions between organisms and their environment is complex. Temperature changes on the order of $1^{\circ}C$ will have some, probably slight, influence on many of these interactions. The total influence of a $1^{\circ}C$ decrease in surface water temperature in summer would therefore be difficult to predict. It is considered unlikely that major changes in biota would occur. Organisms living near their temperature limits would be expected to be effected to the greatest degree. The distributional ranges of some of these organisms may be altered to some extent, particularly in estuaries. A great many organisms inhabit regions in which there will be little or no perceptible change in temperature. These biota will obviously experience no effects.

Water temperatures are also known to vary considerably from year to year. The influence of a $1^{\circ}C$ decrease in temperature may be present but not easily discernible above background variations.

e. Altered fish migration patterns

A decrease of summer surface water temperature on the order of $1^{\circ}C$ in some regions could influence fish inhabiting surface waters during that time of year. It is well known that some fish, such as the

bluefish, tend to enter the northern Gulf of Maine waters sporadically when summer water temperatures are high. Even a slight decrease in surface water temperature may reduce the probability that these and other species having similar temperature requirements, will enter into Maine waters in large numbers. Those species of fish that do not inhabit surface waters in summer for significant periods would not be expected to experience attendant alteration of migration patterns.

f. Altered fouling community activities

In the marine environment, marine fouling organisms may attach to surfaces and result in growths that may impede the flow of water over those surfaces. These organisms are commonly found on boats and buoys. On boats the excessive growth of these organisms may create additional drag which slows these vessels. On bouys these organisms also create drag which tends to stress their moorings. Fouling organisms include barnacles, mussels, other invertebrates and seaweeds. Other fouling organisms such as shipworms are capable of physically and chemically boring into wood resulting in extensive structural damage.

An increase in tidal current velocity may could significantly increase the abundance of fouling organisms. Firstly, higher current velocities will distribute planktonic stages of fouling organisms over greater distances. When the flow of water containing fouling organisms is increased over a surface, the probability of attachment to that surface is greater. Secondly, once these organisms are attached, greater water currents would be expected to increase their rate of growth. Filter-feeding organisms such as barnacles or mussels would gain greater supplies of food and would be expected to grow more

quickly. Seaweed growth would also be enhanced by increased current velocity which would increase nutrient supplies and stimulate growth. Together, higher rates of colonization by fouling organisms, combined with potentially higher growth rates, could significantly increase marine fouling.

Decreased surface water temperatures in summer may occur in some regions resulting in lower respiratory and feeding rates. It is likely that temperature influences on the whole would be small compared to the direct influences of current velocity. At present, shipworm abundance is low in Maine due to low water temperatures. Decreasing the temperature should further decrease the occurrence of this harmful species.

g. <u>Vertical transport of water borne substances</u>

The vertical transport of dissolved and particulate substances in the water column is controlled by advective and diffusive forces. Advective forces would be those forces that involve transport or mixing by current activity such as turbulence where a tidal flow encounters frictional resistance while flowing over the bottom. Diffusion refers to the process of one substance mixing with another where the energy for this motion is endogenous and not driven by currents. Depending on the substance and the circumstances, both can be important to the vertical transport of materials in the sea.

A major influence of the altered tidal regime is the increase in current velocities. Where these currents encounter resistance of boundaries near the surface or at the bottom, turbulence is produced. This turbulence will be the most important advective force accelerating vertical mixing and transport of substances. Greater tidal amplitudes

may, however, also have some significant effects on diffusive forces. Dissolved substances such as ammonium often occur in high concentrations in bottom sediments and have distinctive vertical profiles within these sediments. Lowered concentrations of these substances at the sediment surface allow for the diffusion of substances along a concentration gradient, from sediments to overlying waters. Increased tidal current velocity could wash these substances from the sediment surface more quickly, thereby enhancing the diffusive release of dissolved substances to the water column.

Where barriers exist to transport, as sharp thermal stratification gradients of surface waters in summer, increased vertical mixing could break down the stratification and increase vertical transport. In general, the areas in which higher tidally induced current velocity, shallow waters, and marginal vertical stratification occur would be expected to experience the most significant increase in the vertical transport of water borne substances.

h. Increased nutrient supply to surface waters

Increased tidal currents resulting from higher tidal range would be expected to increase nutrient supplies to surface waters. In sediments and deeper waters, the rates of production or regeneration of substances, such as nitrogenous nutrients, often occur at velocities which exceed those of their consumption. As a result, nitrogenous nutrients, such as ammonium and nitrate, reach higher concentrations in deeper waters. Where summer stratification of the water column occurs, the vertical mixing of these nutrients into surface waters is limited. Increased tidally induced turbulence would be expected to bring

additional nitrogenous nutrients from sediments and deep waters into surface waters resulting in increased phytoplankton growth. In a similar manner, the availability of other dissolved nutrient substances to phytoplankton would also be increased.

i. Transport of pollutants to bottom sediments

Increased vertical mixing would tend to transport some types of pollutants to the bottom at faster rates. This vertical mixing would tend to have an important effect on most pollutants in that greater dilution rates would be achieved. On the beneficial side, diluted pollutants tend to have reduced toxicity and potentially result in less harm. However, the negative aspect involves the incorporation of pollutants into the sediments where their toxicity may remain longer. While opinions may differ on this subject, in the event that the pollutant cannot be contained, increased dispersion which results from increased mixing is often considered to be ultimately beneficial for the petroleum industry.

Higher current velocities near the bottom will increase bottom turbulence which will tend to maintain finer particulate substances in suspension. This would keep finer particles from settling on the bottom to be mixed into bottom sediments. Such finer particles could include substances from drilling muds, used for oil well drilling. Higher bottom turbulence could also act to move and mix bottom sediments at faster rates. This would mean that denser or larger particulate substances which do settle to the bottom could be mixed into bottom sediments more rapidly.

Although oil transport in Maine waters has decreased, oil pollution represents one of the most serious environmental threats to Maine waters. Greater vertical mixing processes would tend to disperse oil more quickly into the water column. The short term effect would be that toxic oil components would be released faster and lead to higher concentrations in the upper water column. Residence time of oil components in the water column would, however, be decreased as oil will mix with water column substances and sink to the bottom at faster rates. There, the poorly weathered oil would mix with bottom sediments and perhaps persist for years.

C. INTEGRATED EFFECTS ON PRODUCTIVITY

1. PRIMARY PRODUCTION OF ORGANIC FOOD MATTER BY PLANTS

The production of food matter by plants is the most fundamental and important biological process in the sea and is susceptible to potential change by an altered tidal regime. Plants capture the energy of sunlight through photosynthesis and transform that energy into the chemical energy of organic food matter. This process is known as primary production and supplies essentially all of the biological energy that is used by marine and estuarine organisms. In the sea, minute single celled algal plants called phytoplankton are singly the most important manufacturers of organic food matter. In coastal waters phytoplankton production is supplemented by the large algae (seaweeds or macroalgae), salt marsh plants and the smaller algae attached to shoreline bottoms. The growth and productivity of these plants must be maintained to provide the food source for marine animals.

2. PLANT PRODUCTIVITY AND TIDAL ALTERATIONS

It is clear that for tidal alterations to significantly affect the total primary productivity of the Gulf of Maine and its coastal waters, the offshore marine phytoplankton must be influenced since it is this population that dominates production. Perhaps the greatest affect of altered tidal regime on phytoplankton would be its influence on tidal currents which in turn influence vertical mixing processes that bring nutrients to the surface waters to promote plant growth. In summer, many coastal and offshore waters become stratified due to warmer temperatures at the surface. This stratification reduces the depths to which surface waters mix and limits the upward movement of nutrients from bottom waters to the upper regions for utilization by phytoplankton.

Increased mixing of the surface and deeper waters in summer would result in an increase in primary productivity due to an increase in nutrient supply. To some extent, however, decreased phytoplankton growth could result from their being transported to greater depths where less light is available. The relationship between vertical mixing and primary production in the Gulf of Maine region has been examined by Yentsch and Garfield (1981). Using satellite imagery, it was estimated that while mixed regions constituted only 30% of the area, they produced approximately two thirds of the total primary productivity. Higher phytoplankton production is moreover quite common in fronts between mixed and stratified water masses (Pingree _et al_., 1978). If in winter, however, vertical mixing of surface waters was increased beyond the "critical mixing of depth" for phytoplankton (40-60 m), these plants could have their growth limited by light availability. These

observations demonstrate the relative importance of vertical mixing events in the primary production process.

While increased tidal mixing of both surface and bottom water is anticipated, the magnitude of mixing change remains unknown. The major effect of increased tidal ranges and current velocities may be some degree of growth stimulation of offshore marine phytoplankton. Garrett (1977) considered that greater tidal mixing "might lead to a significantly increased input of nutrient-rich slope water into the Gulf of Maine" where "one might expect an increased inflow to lead to greater biological productivity."

While inshore waters occupy relatively small horizontal areas, their high primary production and varied habitats support extensive, diverse and important populations of fauna. An increase in intertidal seaweed production may be on the order of at least 10%. Tidal currents would also be expected to stimulate the growth of subtidal seaweeds, but the extent of this stimulation is unknown. It is unlikely that growth would be enhanced in excess of 10% for most subtidal seaweeds. Both intertidal and subtidal productivity could also benefit from the removal of dense plant growth to allow new plant tissue to grow. Intertidal salt marsh could experience some gain in production, also on the order of 10%. This growth could in fact be higher due to increased nutrient supply to salt marsh plants. Greater flushing of marsh areas would additionally transport larger proportions of organic matter from marsh areas to surrounding coastal waters. Estuarine phytoplankton populations could benefit in the same way as offshore phytoplankton.

The stimulatory effect of increased mixing could be greatest in shallow estuaries where shallow sill depth prevents the input of large

amounts of colder, nutrient-rich water. Resulting changes in turbidity would also alter light availability, which could influence light-limited phytoplankton and seaweed growth. Lower temperatures of surface waters in summer could also lead to increased fog which could block light and limit plant growth in some regions. As with all primary production predictions, the complexity of oceanographic processes allow only gross considerations in a brief treatment.

3. MAGNITUDE OF BIOLOGICAL CHANGES

A 10% increase in tidal range may be manifested in many ways which will influence biological communities. For many organisms the ways in which these new influences will act and interact are unknown or complex to the extent that it is not possible to predict the magnitude of biological effect with great confidence. After a period of readjustment to a new tidal regime some differences in biological populations may occur. Some species may benefit significantly and others may decline, a very small number of species may appear less frequently or disappear and may be balanced by the appearance of some new species. For many species, however, the change in tidal regime may have no dramatic impact. In general, the character of biological communities would remain much the same. This is not, however, to say that biological regimes will be unaltered. A 10% increase in tidal range will result in changes in current velocities, mixing processes, temperature gradients and primary production. These are among the major driving forces for biological populations and even subtle alterations are likely to be felt by many species.

The changes that many populations will undergo will, in large part, be masked or hidden by the normal variations in the growth and abundance of natural populations. For many biological populations, growth rates, densities and the factors that control them are incompletely known. For example, a 10% increase in the standing stock of scallops might remain unnoticed if stocks were poorly known or yearly variations in abundance were on the order of 20%. Such changes may, however, be significant in that densities have undergone a real long term shift and are not, therefore, just part of the "noise" of the system. Considering the high and diverse productivity in the Gulf of Maine and its coastal waters, and the large area over which impacts may be felt, small changes may be environmentally significant.

4. READJUSTMENT PERIODS FOR BIOLOGICAL POPULATIONS

After a period of instability, many populations influenced by the new tidal regime will return to an equilibrium state with respect to altered physical, chemical, and biological regimes. For some species this new equilibrium may be favorable while for others unfavorable. Many species will experience little major change. The diverse nature of existing flora and fauna in many regions should allow the character of biological communities to remain much the same.

The period of instability could be prolonged in some sedimentary habitats as, for example, salt marshes where marsh levels are critical and slow to respond to an altered tidal regime. Salt marshes are characteristically areas of sediment accumulation where accretion of sediments and marsh levels often keep up with or surpass sea level rises caused by gradual land subsidence or glacier melting (Nixon, 1980).

High marsh areas dominated by Spartina patens demonstrate accretion rates of 2.0-6.6 $mm \cdot yr^{-1}$ (Harrison and Bloom, 1977). While such rates of sediment accumulation can keep pace with slowly rising sea levels, coastal subsidence rates of 9 mm/yr have been observed in "downeast" (northeastern) Maine. Under these conditions, salt marsh is apparently unable to maintain its tidal position and shows signs of erosion (J. Kelley, pers. comm.). When tidal range is increased by major barrage construction in the Bay of Fundy, marsh erosion is likely to substantially increase.

5. TIDAL PLANT CLOSURE

If and when the proposed tidal power facility is closed and/or dismantled, the tidal regime may well revert to one with a lower range. This would also result in some instability and stress as some biological populations will again have to adjust to new tidal regimes. For some organisms this readjustment to a new equilibrium may procede with no major difficulties. For other regions, such as upper salt marshes, the higher tidal amplitude would have allowed for the increased build up high marsh soil levels. If tidal amplitudes were allowed to fall at the end of the project, much of this remaining high marsh, which is dominant in Maine (Nixon, 1982), may be lost to colonization by plants of upper salt marsh borders. This would very much change the character of such marshes and lead to expanded land areas at terrestrial borders. It is, therefore, clear that the effects of eventual closing of the tidal power facility should be considered.

IV: SOCIO-ECONOMIC CONSEQUENCES

A. INTRODUCTION

Maine's coastal area is the location of a wide variety of activities and structures which play important roles in the State's economic vitality and attractiveness to both residents and non-residents. The diversity of coastal uses coupled with the breadth of the potential effects on physical and biological systems makes the assessment of the potential socio-economic consequences of the proposed Canadian tidal power development extremely complex.

A three stage approach was followed in conducting this preliminary assessment of socio-economic consequences. Initially, 118 different types of coastal uses, structures and facilities were identified and examined in relation to 40 physical and biological considerations. Given the large number of possible combinations, the initial list of uses and structures was pared down to 45 more general categories. All investigators involved in some aspect of the overall study rated each of the 45 categories of coastal uses and structures in relation to the 40 physical and biological considerations. Ratings included the identification of the type of impact anticipated (positive, negative or uncertain) and the relative magnitude of the impact (significant, minor, uncertain). The final stage of the assessment involved summarizing and categorizing the results of the ratings.

In reviewing the results of this assessment of socio-economic consequences, the reader should bear in mind the following:

1) The ability to predict accurately the potential socio-economic effects is directly related to the ability to predict the effects of the tidal power development on physical and biological systems;

2) Study constraints did not allow for detailed quantitative analysis of anticipated socio-economic consequences. As a result, the categorizing of the degree of impact on specific coastal uses must be considered preliminary;

3) A number of coastal uses that were evaluated are not included in this discussion because they were not considered to be significant from a statewide perspective. This, however, does not mean that there will be no impacts on these uses of local significance.

The following discussion of the potential effects on coastal structures and uses is composed of four sections, structures and uses subject to 1) major, 2) moderate, 3) minor and 4) uncertain impacts. This loose prioritization is based on the limited qualitative and quantitative data available at this time and the judgment of the author. Re-evaluation of the ratings is absolutely necessary when more detailed socio-economic data and a clearer understanding of the effects of the Canadian project on physical and biological systems are available.

B. COASTAL STRUCTURES AND USES SUBJECT TO MAJOR IMPACT

1. SHORELINE STRUCTURES

Many shoreline structures are likely to be seriously affected as the result of the Canadian project. Residential, commercial, industrial, institutional and governmental structures located along Maine's coast will be affected by landward movement of the high tide line, increased penetration of storm tides and increased flooding of low-lying areas. These effects will be long-term in nature and may have a negative effect of substantial magnitude.

Landward movement of the high tide line will result in the undermining of some structures located immediately adjacent to the shoreline. Lawns, driveways and parking lots in some locations are likely to be damaged. Some structures may have to be moved or reinforced.

Increased penetration of storm surges and increased flooding of low-lying areas is likely to result in a significant increase in the amount and frequency of damage that occurs to coastal structures during storms. For example, the 1978 winter storm that caused 47 million dollars in property damage along Maine's coast is considered to have been a 100 year recurrence interval storm. In other words, a storm of that magnitude under present conditions is likely to occur once every 100 years. As the result of changes in the tidal regime, water levels produced by storms of the magnitude of the 1978 storm would be expected to be produced by storms every 25 years.

2. FEDERAL FLOOD INSURANCE PROGRAM

The Flood Disaster Protection Act of 1973, PL 93-234, requires communities throughout the country to participate in the National Flood Insurance Program if they have a flood hazard area within their boundaries. Under the program, individuals who wish to borrow money from a federally insured lending institution to build or buy a structure in a flood hazard area are required to purchase flood insurance.

The program consists of two phases, the emergency program and the regular program. Under the emergency program, flood insurance is provided to property owners at a rate subsidized by the government. Once a detailed engineering study of a community has determined precise flood elevations and actuarial rates, the community has six months to

enact a detailed flood hazard ordinance and become part of the regular phase. Flood insurance remains available at subsidized rates for pre-existing structures, but new structures and structures which are significantly expanded or altered may only be insured under actuarial rates.

The Flood Insurance Program may be affected in a number of ways due to the landward movement of the high tide line, increased penetration of storm tides and increased flooding of low lying areas. Engineering studies that determine flood insurance rate maps may have to be reworked. Between 25 and 75 such studies may have to be revised at a minimum cost of $15,000 per study. Coastal property owners are likely to be faced with a higher cost for flood insurance under the regular program due to the increased potential for storm damage. The cost to the federal government of subsidizing flood insurance could increase significantly as the result of the possibility of increased storm damage.

The federal government could incur substantial claims under this program. As of June, 1982, there were 3,047 policies in effect along the Maine coast. The total amount of the insurance was $105,078,100.

3. PROPERTY VALUE

Maine's 6705 km of shoreline (Topinka and Korjeff, 1981) is one of the state's most attractive and valuable physical assets. This portion of the state is the location of a substantial amount of the State's residential, commercial and industrial use of land. Maine's shoreline represents hundreds of millions of dollars of property value and is an important component in the state's tax base.

Property value along Maine's coast may be affected by the proposed Canadian tidal power development in a number of ways. The effects may be of both a short-term and long-term duration and are likely to affect both individual property owners and government.

The landward movement of the high tide line is likely to permanently affect property value through the physical loss of presently taxable land. Due to the physical characteristics of Maine's coast, the southern coastal area is likely to be most seriously affected. This portion of the coast is very intensively used for residential, commercial and industrial purposes. The value of the structures that may be adversely affected raises the potential for permanent loss in property value.

Increased penetration of storm tides and the flooding of low lying areas are also likely to have an effect on property value along the coast. In some instances, storm-related property damage is likely to result in the permanent removal of existing shoreline structures. While it is difficult to estimate the potential, permanent loss in property value resulting from increased coastal storm damage, the figure is likely to be in the millions of dollars.

The permanent loss of property value would affect government as well as the private property owners. Government would lose property tax revenue as the result of lower assessed valuations of coastal property.

Coastal property values may also be affected by the perceived threat to such property from the landward movement of the high tide line and the potential for increased storm damage. The lowering of property value because of these threats will affect most acutely people wishing to sell their coastal property. It is unlikely that municipal

government will move quickly to readjust property assessments due to this consideration thereby minimizing the resulting property tax loss.

The lowering of coastal property value due to the perceived threat from the landward movement of the high tide line and increased storm tides would be temporary in nature. Once a new geomorphological equilibrium is reached and is recognized, the negative effect on property values is likely to cease.

4. TOURISM

Tourism in Maine makes a substantial contribution to the state's economy. In 1981, tourism related expenditures were estimated to be 600 million dollars. These expenditures sustained the equivalent of 20,000 full-time jobs.

Tourism along Maine's coast accounts for a significant portion of the tourism that takes place within the State. A primary attraction of Maine's coast to tourists is the recreational opportunity that exists. Recreational activities are likely to be affected by the anticipated changes resulting from Canadian tidal power development.

Recreation on Maine's 36 miles of major sand beaches (Nelson and Fink, 1978) could be affected by a number of changes that take place as the result of Canadian tidal power development. Landward movement of the high tide line, expansion of intertidal areas, and reduced air and water temperature are likely to produce the most significant effects.

Landward movement of the high tide line is likely to have a negative effect on beach recreation on a short-term basis. In the short-term, landward movement of the high tide line could result in a smaller sand beach area above the high tide line. Since this is the

most desirable location for beach recreational use, the short-term capacity of beaches to accommodate people would be decreased. Also, the undermining of land and structures adjacent to beach areas as the result of higher high tides and increased storm damage could result in the deposition of debris on beaches. This would decrease the physical space available for recreational use and may negatively affect the attractiveness of beaches to recreational users.

In the long-term, the effect of the landward movement of the high tide line on beach recreation will be dependent on the presence of seawalls. Where seawalls are not in existence, there will be a landward movement of the entire dune/beach system to the point where a new equilibrium is reached. Under the new equilibrium, the beach is likely to be slightly larger in size to what existed prior to the movement of the high tide line, thereby providing increased beach recreational opportunity. However, in areas where seawalls are present, the natural migration of the beach system will be obstructed resulting in a permanent loss of high tide beach area. In some places, such as Higgins Beach in Scarborough, the landward movement of the high tide line is likely to eliminate completely the presence of any sand beach area during high tide periods. This would obviously have a permanent, negative effect on beach recreational opportunity and use.

Reduced air temperature and increased periods of fog resulting from reduced water temperature are likely to result in a decrease in the time during the summer when beach recreational use is an attractive activity. While the exact magnitude of the impact is difficult to assess at this time, the magnitude is expected to be relatively minor. However, since weather is such a critical factor in determining the success of Maine's

short, summer tourist season, any decrease in recreational user days is undesirable.

Swimming may be affected by lower air and water temperatures and stronger tidal currents, resulting in a long-term, negative impact of minor significance. Lower air and water temperatures as well as an anticipated increase in periods of fog would result in a decrease in the number of days during the summer when swimming in coastal waters will be desirable. Stronger tidal currents could discourage some people from swimming in coastal waters. The magnitude of these potential impacts is unknown but may be minor.

Sailing and canoeing along the coast may be affected on a long-term basis in both positive and negative ways. Positive consequences include stronger and longer lasting on-shore breezes which should be to the benefit of sailing. Increased periods of fog will result in a decrease in the number of days during which sailing and canoeing are considered desirable pursuits.

The major influences on motorized boating will be increased periods of fog, lower air temperatures, and stronger tidal currents which may make maneuvering more difficult. While these influences will be long-term in nature, they are likely to be minor in magnitude.

Aesthetic enjoyment is very subjective. Therefore, it is extremely difficult to assess whether anticipated consequences would be positive or negative in nature. Two long-term changes that may take place which may affect recreational pursuit include increased periods of fog and expansion of intertidal area.

At this time, the balance of potential effects on tourism appears to be in the direction of a negative impact. This is particularly true

along the "beach belt" in southern Maine. The magnitude of the negative effect on tourism is difficult to predict at the present time.

It should also be noted that the diminishing of recreational opportunity along Maine's coast may negatively affect the ability of Maine's residents to satisfy their demand for recreational pursuits. This may result in the need for increased expenditures by state and municipal government to expand public recreational opportunity.

C. COASTAL STRUCTURES AND ACTIVITIES SUBJECT TO MODERATE IMPACT

1. ROADS

There are a number of locations along the coast where landward movement of the high tide line, flooding of low lying areas and increased storm tide penetration are likely to affect state, town and private roads. Some roads may be undermined resulting in the necessity for reconstruction and/or relocation. Others may be subject to a greater likelihood or more frequent flooding. The most serious problems are likely to exist along the southern portion of the coast, although scattered locations along the entire coast may be affected.

While the changes in high tide line, storm surges and flooding of low lying areas will be long-term in duration, alterations in road location and structure are likely to take place in the short-term, thereby solving most road associated problems.

The cost of making the necessary road alterations is difficult to assess at this time. It is likely, however, that the expense will range in the millions of dollars. Town and state government would incur the expenses in the vast majority of cases.

Examples of road areas likely to be adversely affected include: the Manset-Seawall area of Mt. Desert; Routes 1 and 9 and the Black Point Road in Scarborough; Route 123 in Harpswell; Shore Road in Cape Elizabeth; the Mile Road and Drakes Island Road in Wells; and Route 1A in York.

2. SHORELINE STABILIZATION STRUCTURES

Seawalls are located along fourteen of Maine's thirty-six miles of major sand beaches (Nelson and Fink, 1978). Additionally, there are numerous miles of coastline where rip-rap and other shoreline stabilization structures have been put into place to prevent shoreland erosion. These structures are maintained by private individuals and local, state and federal governments.

Shoreline stabilization structures are likely to be adversely affected along the entire coast of Maine. The structure and function of shoreline stabilization structures are most likely to be affected by the landward movement of the high tide time, increased penetration of storm tides and changes in erosion/deposition patterns. The magnitude of the problem and the cost of mitigation cannot be estimated based on the current level of investigations.

3. ARCHEOLOGICAL AND HISTORIC SITES

From an archeological perspective, Dr. Arthur Spiess of the Maine Historic Preservation Commission has stated, "Basically, a 6 inch tidal amplitude increase would be a disaster." Coastal erosion is considered to be the worst, current threat to Maine archeology. Approximately 1,400 of 2,129 sites included within the Commission's inventory are

located along the coast. As many as 700 shell heaps and other coastal sites would apparently be lost due to the predicted tidal regime changes.

Dr. Spiess roughly estimates that it would cost around 5.5 million dollars to excavate sites that would otherwise be lost. Alternately, the installation of erosion control walls at 700 sites would cost approximately ½ to 1½ million dollars. Additionally, the change in the tidal regime might destroy some sites that have not yet been identified.

Concerning the possible advantages from an archeological perspective of lower low tides, Dr. Spiess stated, "6 inch lower low tide will not add anything to our knowledge."

Many of Maine's historic sites are situated along the coast. Some of these sites may be affected by the landward movement of the high tide line, increased penetration of storm surges, and the flooding of low lying areas. Sites potentially affected include those of national, state and local significance.

4. ON-SITE WELLS

As discussed earlier in this report, increased tidal range may affect the groundwater hydrology of the coastal area and subsequently increase problems of salt water intrusion into drilled wells. The increase in problems associated with salt water intrusion would be permanent in nature. Twenty-four of the one hundred thirty-one municipalities along the coast have some problems associated with salt water intrusion while six have more severe problems (Caswell and Ludwig, 1978). The magnitude of these problems is very likely to increase. Individuals with unsatisfactory water supplies may experience difficulty

in meeting their basic water needs as well as a potential decrease in the value of their property. New construction on undeveloped land may be deterred due to difficulty in securing a satisfactory on-site water supply. Communities within which problem areas are located are likely to experience either a lowering in property tax revenue from certain properties due to reduced property value or pressure to spend municipal funds to establish public water supplies.

The surface damage to wells and water supply integrity resulting from landward movement of the high tide line and increased flooding of low lying areas during storm tides is likely to be a much less significant problem. The problem will be short-term in duration and will most likely have to be dealt with by private individuals.

D. COASTAL STRUCTURES AND ACTIVITIES SUBJECT TO MINOR IMPACT

1. PARKS, TRAILS, REST AREAS, BOARDWALKS

Landward movement of the high tide line, increased penetration of storm surges, and flooding of low lying areas is likely to affect parks, trails, rest areas and boardwalks along Maine's coast. Some trails and boardwalks may have to be relocated. State and municipal beaches may be either temporarily or permanently affected depending upon the beach systems ability to naturally migrate landward as the high tide line advances. Stabilization of newly eroded areas may be necessary. Scattered areas along the entire coast are likely to be affected although the number of parks, trails, rest areas and boardwalks affected by anticipated changes is not expected to be large. The cost of making any adjustments would have to be borne by state and local government and private individuals.

2. BOAT RAMPS

Public and private boat ramps may have to be extended in order to accommodate the lowering of low tide. Ramps may also be affected by the landward movement of the high tide line and increased penetration of storm tides. The need for erosion control measures may therefore result. This will vary depending upon the location and structure of ramps.

3. SHORELAND ACCESS

Under the Colonial Ordinance, all citizens in Maine are provided legal access to the intertidal zone in order to pursue certain prescribed activities. This right prevails regardless of whether the area is in private or public ownership. As the result of the lowering of low tides, the public will have access to a larger intertidal area.

Expansion of the intertidal area may also provide the public with some, perhaps minor, increased opportunity to gain access to private lands that are presently protected by tidal waters. For example, there are some islands along the coast which are currently barely accessibly by foot at low tide. Lower low tides would allow greater access to such areas.

4. PROPERTY BOUNDARIES

The landward movement of the high tide line and the seaward movement of the low tide line would result in changes in the boundaries of shorefront property. These changes may result in the need to reconstruct municipal property maps or at least to reassess coastal property. This could be a significant undertaking particularly along

the southern portion of Maine's coast. The responsibility and cost of doing this work would fall on municipal government.

5. SEARCH AND RESCUE

Stronger offshore currents and the possibility of increased periods of fog could be long-term consequences affecting search and rescue missions. The area to be searched would have to be larger due to greater drifting resulting from stronger currents. More fog would affect visibility in making sightings.

6. POLLUTION ASSIMILATION

Increases in tidal currents may have a beneficial effect on pollution assimilation in coastal waters. Flushing rates are likely to increase. This effect should be evident to varying degrees along the entire Maine coast.

7. NAVIGATIONAL MARKERS, MOORINGS AND FLOATS

Navigational markers, moorings and floats will be influenced by four factors: the change in the tidal regime, increased tidal currents, increased fouling community activity, and changes in ice accumulation characteristics. Markers, moorings and floats may have to be relocated to reflect changes in the tidal regime. They may have to be more securely moored due to increased tidal currents. Maintenance may have to be more frequent due to increased fouling community activity. Changes in ice accumulation characteristics could result in increased damage to markers, moorings and floats due to larger and more ice floes

moving at higher velocities. These ice floes may also subject moored boats to increased potential to damage.

Moorings may have to be realigned to provide more space between vessels, thereby decreasing a harbor's capacity. This could result due to faster tidal currents and greater wave activity in back bay areas. It would also be influenced by the need to make moorings longer due to the greater tidal fluctuations.

8. NAUTICAL CHARTS, TIDAL CHARTS, AND CURRENT PREDICTIONS

The National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, publishes tide and tidal current values in a series of publications. These publications include "Tide Tables, East Coast of North and South America," "Tidal Current Tables, Atlantic Coast of North America," and "United States Coast Pilot, Atlantic Coast: Eastport to Cape Cod."

According to Capt. W.V. Hull of NOAA's Office of Oceanography: "If the barrage is built, the values presented in the above-mentioned products will have to be verified and modified, if required. This requires that the Canadian government confirm the data transmitted to NOS are correct. NOS will have to collect at least 5 years of tide data at Eastport and Portland, Maine, to ensure that seasonal differences are accounted for in the predicted values. Each of the secondary stations will have to be redeployed, processed, and analyzed. A minimum of 2 project years is required to obtain the necessary current meter data, then these data must be processed and analyzed. The results of the tide and tidal current analysis will then have to be incorporated in these products." NOAA has estimated that the cost for updating the tide data

and the current data would be \$600,000 and \$2,000,000, respectively. Additionally, NOAA publishes nautical charts which would have to be updated. No estimate has been obtained for the cost of doing this.

E. COASTAL STRUCTURES AND ACTIVITIES SUBJECT TO UNCERTAIN IMPACT

1. SHELL-FISHING

Shrimp, lobster, crab and scallop industries may be influenced by a change in tidal regime. The acceleration of tidally induced current velocities is likely to increase vertical mixing processes and stimulate primary productivity. This productivity could be of benefit to populations of shrimp, lobsters, crabs and scallops. It is doubtful, however, that such population effects would be large relative to natural cycles in abundance.

2. CLAM, WORM AND MUSSEL HARVESTING

A 10% increase in tidal amplitude would be expected to increase intertidal mudflat and other regions over which soft shelled clams, mussels and worms are harvested. If, after shore line re-equilibrium is reached, mudflat area is increased by 10%, a 10% in the standing stock of these organisms may be anticipated. In the short-term, after the tidal amplitude is increased, harvesters could harvest potentially productive low water regions with greater ease.

The greater current activity would also be expected to increase the primary production of food matter by phytoplankton, seaweeds and marsh plants which would benefit the growth of clams, worms and mussels. Higher current activity would also be expected to bring food matter into suspension in the water column which would benefit filter feeding

animals, such as clams and mussels. Increased current velocities would also tend to bring more food past stationary filter organisms, increasing growth rates.

On the detrimental side, lower water temperature in summer would be expected to decrease feeding activity and could decrease growth. Additionally, red tide contamination would be likely to increase the toxicity of both clams and mussels.

From all this, it must be concluded that populations of clams, mussels and worms may be influenced in many complex ways by an altered tidal regime. Further, this level of influence will vary in degree with different regions. In conclusion, it appears that the clam, mussel and worm populations may well experience gains approaching 10% in standing stocks after the rearrangement of sediment distribution in some mudflat areas. The relative magnitude of change in the red tide problem cannot easily be approached other than to state that the red tide toxicity of mussels and clams is likely to increase.

3. FIN-FISHING

Fin-fishing in the Gulf of Maine is primarily conducted using an otter trawl, i.e. dragging. The several fishing boat captains interviewed shared the view that newer boats are built with marginal power because of the cost of fuel. Fishing is the best at spring tides and the boat's ability to fish these currents is, at present, limited by their power. These captains stated, in various degrees of vehemence, that an additional 5-10% in tidal current strength would severely limit or curtail their capacity to fish at spring tides.

4. ANADROMOUS FISHING

Anadromous fish swim up estuaries to spawn. They are subjected to estuarine conditions and the associated influences of an increased tidal amplitude. While tidal currents will be increased and will be more difficult to swim against, when the tidal flow is reversed, fish will make additional headway with the aid of tidal currents.

The influence of potentially decreased water temperature in summer could pose no great problem for many organisms over relatively short durations. Increased estuarine flushing would be expected to increase salinities near the heads of estuaries. The distribution of food organisms along the route would also be expected to be shifted up toward the heads of estuaries. While no major interference with anadromous fishing is anticipated due to these influences, see, however, the section entitled "Altered fish migration patterns."

5. SEAWEED COLLECTION

A 10% increase in tidal amplitude should increase the area over which rocky intertidal seaweeds grow by 10% due to a greater habitat availability. This alone should increase the intertidal seaweed biomass by 10%. Included would be an increase in the intertidal standing stock of Irish moss (*Chondus crispus*) and rockweeds (*Ascophyllum nodosum* and *Fucus* sp.) which are among the most commercially valuable plants. While subtidal seaweeds are not extensively utilized along the Maine coast, large populations of kelp exist and will soon be exploited. The use of seaweeds as a nutritional food source is also expanding. These populations, however, would not be directly affected by a change in the tidal range, except for some decrease in the uppermost subtidal which would be

occupied by intertidal organisms. Both intertidal and subtidal seaweed populations could, however, experience greater growth rates due to increased current velocities and the upwelling of plant nutrients from deep, colder waters.

6. AQUACULTURE

The major aquaculture industries in Maine involve mussels and oysters. Higher primary production of organic food matter by plants, greater suspensions of organic matter from the bottom, and higher rates of water flow past these organisms should increase feeding. This would result in an increased growth rate. A potential decrease in icing conditions in regions of greater current velocities would also be of some benefit to these industries. As previously discussed, there is the possibility that red tide problems might be increased. Mussels, clams and oysters would be subjected to potentially greater blooms of red tide and could be exposed to greater numbers of red tide cysts. Ingestion of either motile, growing organisms, or cysts could increase shellfish toxicity (Lewis et al., 1979).

7. MARINE TRANSPORTATION

Stronger currents may have an effect on the cost of marine transportation. Greater fuel consumption could take place when movement occurs against the current. Conversely, savings might be gained when movement is in the same direction as the current. Also, the stronger currents could affect the amount of time it takes to travel from one port to another. Travel time will depend on the direction of the movement in relation to the currents.

Stronger currents may also affect ship maneuverability in close spaces. Existing turning basins may not be sufficient to accommodate the increased currents. The general shift in the tidal regime may affect both the ability of boats and ships to gain access to docking and mooring areas and the loading and unloading of passengers and cargo. Lower low tides are likely to have a negative effect on accessibility to docking and mooring areas and could result in time delays in shipping. Higher high tides will increase accessibility to previously marginal or inaccessible areas. The gradient between boats and docks will be greater than is presently the case at high and low tides. This could create problems in certain instances. For example, the Frenchboro ferry presently has difficulty with loading ramps at low tide.

Inlet stability is expected to be affected by the tidal power development, though the exact nature of the effect is not clear. The effect of inlet instability on marine navigation is likely to be short-term since a new equilibrium in inlet stability would eventually be reached. Natural inlets are likely to be more greatly affected than fixed tidal inlets.

A longer term effect of inlet stability on marine transportation involves the possibility that the deepening of fixed tidal inlet channels might result in rougher waters within harbors. This, coupled with an increase in tidal currents, could increase the difficulty of ship maneuvering within harbors.

Changes in patterns of ice accumulation might also affect marine transportation within harbors and tidal river channels. This would be both positive and negative as the channel itself would be less prone to

icing due to increased tidal currents, but more ice floes could be expected due to greater accumulation of ice in intertidal areas.

Changes in the erosion-depositional patterns may affect the depth of navigational channels, turning basins, anchorages and mooring areas. At this time, the nature of potential changes is not understood well enough to predict the effect on marine transportation.

8. NAVIGATIONAL CHANNELS

The overall effect of Canadian tidal power development on navigational channels is not clear at the present time. The predicted change in tidal range would result in a 15 cm increase in channel depth at high tide and a 15 cm decrease in depth at low tide. At the same time, while increased tidal currents may result in the deepening of some channels, possible changes in erosion-depositional patterns could negate potential positive effects. Changes in physical characteristics within the Gulf of Maine could potentially influence the shape, depth and width of some channels. More frequent dredging of some channels and first-time dredging of others may be necessary.

9. PIERS AND DOCKS

Piers and docks are likely to be affected by higher high tides, increased height of storm tides, changes in tidal currents and changes in ice accumulation. Public and privately owned piers and docks along the entire coast may be affected. The magnitude of the impact on individual piers and docks is likely to vary depending upon design and location.

Higher high tides could result in some piers and docks being awash. Increased exposure to salt water could affect the deterioration rate of construction materials. Mechanical equipment associated with piers and docks might suffer from increased contact with salt water.

Increased penetration of storm tides could result in an increase in storm damage of piers and docks on a more frequent basis than presently experienced. Faster tidal currents could affect the structural stability of some docks and piers. Greater accumulations of ice in the intertidal zone coupled with stronger currents may result in more structural damage to piers and docks in the springtime.

The cost of making necessary structural modifications and repairs would have to be borne by both the public and private sectors.

10. BREAKWATERS AND JETTIES

Higher high tides and changes in tidal currents may result in the need to modify the design and structural stability of breakwaters and jetties. Design modifications may be necessary in order for the structures to continue to perform their intended functions. Structural stability may be affected by increased height of storm tides, changes in tidal currents and changes in ice floe characteristics.

11. BRIDGES

Higher high tides, increased tidal currents, increased force of ice-out and increased penetration of storm tides could have an influence on bridges along the coast. In general, steel and concrete would have greater exposure to salt water resulting in a faster rate of deterioration. Culverts may not be sufficient to carry increased

volumes of water at increased velocities. Swing bridges, especially those with little clearance over the existing high tide line (i.e. Gut Bridge in South Bristol) may need special protection from salt water to protect working mechanisms. Rip-rap embankments may need work as the result of higher high tides, faster currents and greater potential for storm damage.

The lowering of low tide would make bridge related repairs easier since the water level would be lower and more time for repairs would be available.

12. RAILWAYS

Some low-lying railway lines along the coast may be affected by the higher water level which may result if major storm surges are coincident with high tides. The cost of relocating or repairing tracks could be significant. Damage did occur to tracks in Portland during the 1978 storm.

13. UNDERGROUND UTILITIES AND TRANSMISSION LINES

Underground utilities and transmission lines located close to the shoreline may be adversely affected due to the landward movement of the high tide line and increased penetration of storm tides. Utilities may be undermined or exposed to increased potential for damage from storms. Some utilities may have to be relocated.

14. OIL SPILL CONTAINMENT

Increased coastal and offshore currents, greater vertical mixing and deeper inlet channels may have a long-term effect on the ability to

contain oil spills. Increased tidal and offshore currents and the "roughening" of bays due to the deepening of stabilized inlets could make the use of booms to contain spills less effective than is presently the case. Also, due to greater vertical mixing, oil would be dispersed quicker which would be positive. The faster release of oil components lead to higher concentration over a shorter period in the upper water column. To a great extent, oil spill dangers have decreased with decreased oil transport along Maine (D. Murch, pers. comm.).

15. SANITARY AND STORM SEWER OUTFALLS

A number of communities in Maine have sanitary and/or storm sewer outfalls that discharge directly into tidal waters. The design parameters for these outfalls were based on the currently experienced tidal regime and storm tide characteristics. Higher high tides and increased storm tides may cause effluent to back up in the system, possibly breaking out to the surface through manholes.

The potential for the occurrence of the problem outlined above will be long-term in duration. The magnitude of the problem is not clear at the present time. A study of existing sanitary and storm sewer systems along the coast will be necessary to identify the potential for such occurrences and the cost of taking mitigative action.

16. SEWAGE TREATMENT FACILITIES

A number of communities in Maine have sewage treatment facilities located in close proximity to tidal waters. Some of these facilities may be affected by the landward movement of the high tide line and

increased height of storm tides. A study of each facility would be necessary to determine if any problems will arise.

These facilities may benefit from an increase in the flushing rate of tidal waters.

17. LOBSTER POUNDS

Fifty-two lobster pounds providing 4½ million pounds of lobster are located along Maine's coast. Pounds may be influenced by increased flushing rates, changes in the tidal regime, increased ice accumulation in the intertidal zone, landward movement of the high tide line, increased height of storm tides and changes in water temperature. The exact influence of Canadian tidal power development on lobster pounds is unclear at this time.

V: RESEARCH NEEDS

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TABLE OF CONTENTS

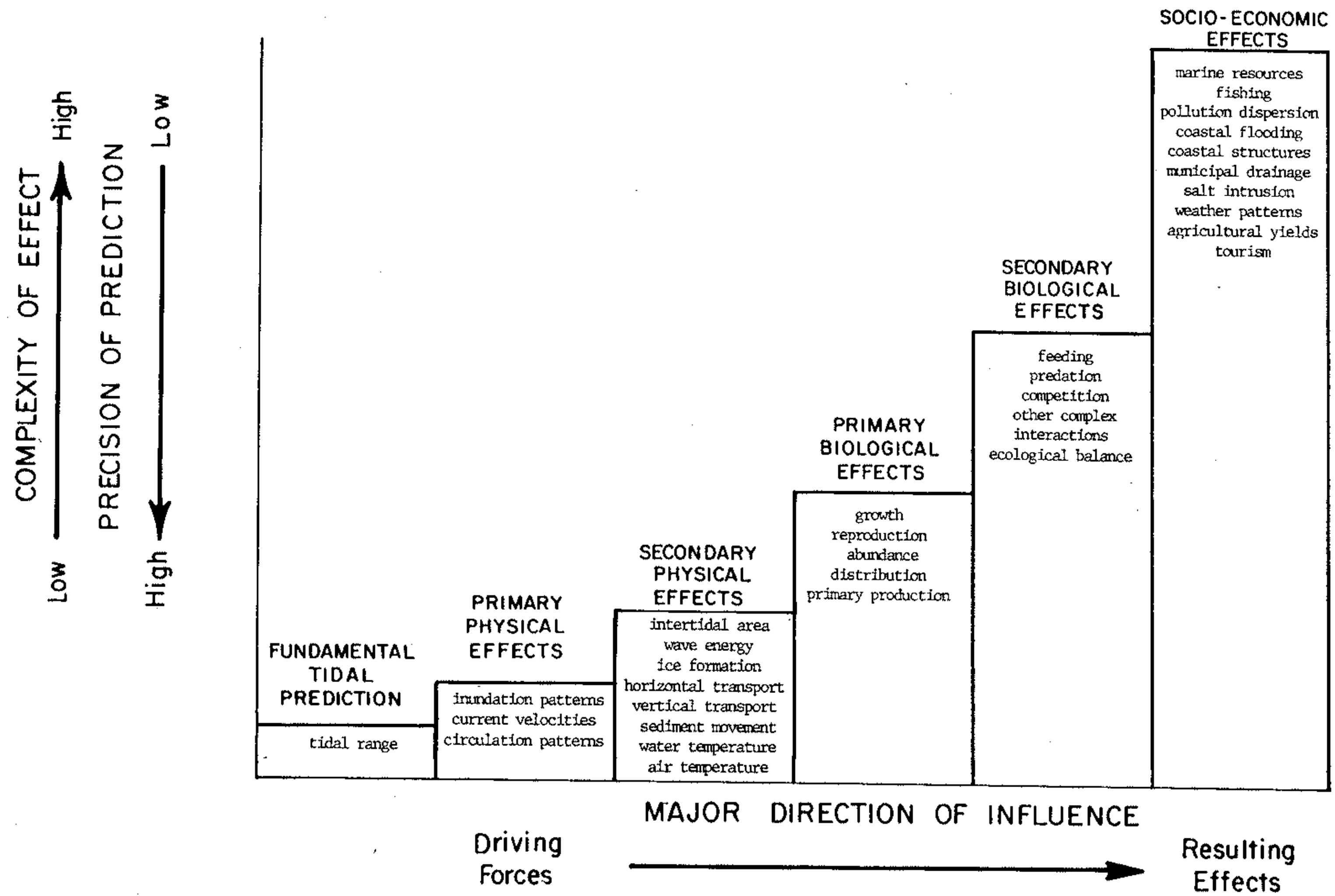
A. RESEARCH OVERVIEW

An examination of the potential effects of an increased tidal range on the Maine coast emphasizes our need to know more about the fundamental mechanisms that are important to estuarine and marine systems. While it is possible to make general statements concerning the types and gross magnitudes of potential effects due to Bay of Fundy tidal power development, quantitatively rigorous treatment of many areas of concern is often scientifically impossible at this juncture. There is little doubt that we need to know, in greater detail, how an increased tidal range will impact the people of Maine, their economy and their environment. To do this, however, it is important to realize that a knowledge of the environmental effects is basic to our understanding of major economic influences. It is clear, therefore, that we must first consider what fundamental processes of estuarine and marine systems must be better known to resolve the tidal impacts on Maine.

It is important to gain a conceptual understanding of the extent to which environmental influences can be predicted. In Fig. 7 we explore 1) the increasing complexity of physical, biological and socio-economic effects, 2) the dependence of more complex effects on fundamental physical and biological changes, and 3) the association between more complex effects and the difficulty of their precise prediction.

The fundamental change in tidal range will produce primary physical effects which yield secondary physical effects. These physical effects structure primary and secondary biological effects, all of which in turn, influence socio-economic effects. This demonstrates that many of the more complex biological and socio-economic effects cannot be approached without knowledge of the basic forces that drive complex

Fig. 7. HIERARCHY OF TIDAL INFLUENCES, THEIR POTENTIAL EFFECTS AND THE PRECISION WITH WHICH THEY CAN BE PREDICTED



responses. One cannot, for instance, make precise fisheries predictions without a fundamental knowledge of basic physical and biological effects and an understanding of fisheries production.

It is also clear that as we proceed from fundamental tidal predictions through primary and secondary physical and biological effects to socio-economic effects, each succeeding category of effect becomes dependent on a greater number of basic tidal and non-tidal effects. This situation renders biological and socio-economic effects exceedingly complex and more difficult to predict.

This leads us to the question of what needs to be known and what predictions can be made with greater confidence. From the preceding discussion, it is apparent that many primary physical and biological effects must be quantified to serve as the basis to understand more complex biological concerns and socio-economic issues. In terms of what predictions can be made with greatest confidence, our hierarchal system in Fig. 7 demonstrates that the more basic or primary physical or biological predictions will have a higher degree of precision. No prediction can have a greater level of precision than the estimate upon which it was based. It must, therefore, be realized that many of the more complex biological and socio-economic concerns may never be predictable with as high a precision as we would like.

All this, however, is not to suggest that we should concentrate only on more fundamental or primary effects, but rather that the answers to more complex environmental and socio-economic effects must be pursued together with the basic mechanisms which give rise to complex concerns. It is clear that many tidal effects need to be considered and, if possible, predicted within the next few years in order to allow U.S.

agencies to respond to Canadian plans before engineering plans are finalized and commitments for construction are made. It is therefore imperative that we push forward on all research topics, thereby developing parallel or more preferably, integrated programs to evaluate the entire spectrum of responses which may be of importance.

B. RESEARCH PRIORITIES AND INDIVIDUAL RESEARCH PLANS

At our present state of knowledge, we cannot precisely rank the importance of all potential impacts or research needs. It is, however, possible to rank impacts and research needs by placing them in broad categories. We have therefore ranked research needs in the following categories: "High Priority Research Needs" and "Medium Priority Research Needs." High and medium priority research needs are outlined below. The large number of low priority research needs are not presented. It must be emphasized that priority ranking is somewhat arbitrary and the ranking of individual research needs will and should change as we develop deeper insight into tidal power issues.

It was the request of the State Planning Office that we prepare various individual and collective options for fulfilling research needs. We have therefore presented recommendations both in terms of individual research needs or priorities and in the form of an integrated plan of research. The list of individual research needs would allow individual investigations to be pursued. As discussed later in this section, however, many of these research needs would most efficiently and effectively be considered in a single integrated research program for which a time frame and budget are also provided. If funds are available, we strongly recommend the integrated research plan which can

be supplemented by other individual programs outlined under the following sections dealing with high and medium priority research needs.

1. HIGH PRIORITY RESEARCH NEEDS

a. An examination of tidal predictions. Tidal predictions are central to all tidal effects, thus it is desirable to develop wider and greater understanding of these predictions. New, and perhaps important, perspectives may be provided by engineering sectors. It is suggested that physical oceanographers familiar with Greenberg's model, together with other scientists from both private and government sectors, participate in a 2-day workshop to evaluate the Greenberg model and its tidal predictions. Representatives of these groups would be charged with assembling a detailed report, together with a short simplified summary of their evaluation. This rapid and low-cost effort represents, in our opinion, the best mechanism to examine the Greenberg model and heighten the awareness of those who would use its results. If results suggest that the construction of another, more precise, major model is necessary and possible, such an effort should be undertaken. This important step should be undertaken as soon as possible (estimated cost: $18,000; duration: 4 months).

b. An investigation to produce more detailed tidal predictions in offshore, coastal and estuarine regions. Tidal predictions are needed to assess environmental effects. It will prove valuable to obtain these predictions on a fine scale or grid in order to provide the more detailed tidal changes which are required for the more precise prediction of environmental

alterations. The Greenberg tidal model should be employed to make these detailed tidal predictions. Greenberg's present grid size for the tidal predictions in the Gulf of Maine is presently 21.14 km, which should be reduced to approximately 7 km. Dr. Greenberg has 7 km grid data, which, after being made compatible with original Minas Basin data, may feasibly be used to produce more detailed tidal predictions.

There is also a need to produce highly detailed tidal data for Maine estuaries. Physical models for major embayments should be constructed and linked to Greenberg's coastal data to provide high resolution tidal predictions. These efforts should be conducted in conjunction with the following physical investigation.

c. <u>The prediction of tidally induced changes in current velocities, vertical mixing intensities, water temperatures, and circulation patterns</u>. While predictions of tidal amplitude will provide the fundamental tidal data, the degree to which an altered tidal amplitude will change other primary physical features must also be known. Using the Greenberg model and models of coastal embayments, predictions should be made of current velocities, vertical mixing intensities, water temperatures and circulation patterns. These parameters should be predicted on the same detailed scale as the above tidal range predictions. To the extent possible, predicted changes in tidal amplitude, current velocities, vertical mixing intensities, and current patterns should be investigated and understood in the context of driving forces other than tidal

action. The actual cost of this effort and that to produce the fundamental tidal predictions will closely reflect greater data acquisition for smaller grid sizes and increased modelling efforts (estimated cost: $800,000; study duration: 4 years).

d. A study of shore line structure, the physical extent of increased shore line flooding, and its resulting biological implications. Changes in intertidal area will occur as the result of a larger tidal range. It is necessary to know how much the various intertidal habitats will be changed in terms of area. How much area will be lost from subtidal and terrestrial borders? What is the response time of the various sedimentary environments? How will the gains and losses be distributed among various segments of the coast? The distribution of biological populations in intertidal areas are structured by patterns of tidal inunation. What will be the biological responses to the a new tidal regime? What will the new equilibrium be and what will be the implications for commercially and ecologically valuable biological components?

Aerial photography and remote imagery from aircraft may be used to determine the extent to which characteristic intertidal regions on these major biota will be inundated. This effort would be conducted at intervals over the tidal cycle. Such information would be correlated with ground level examination of shore line profiles of water height, slope and sediment type. Biological transects would be employed to determine present zonation patterns relative to tidal inunda-

tion. These biological data would be used in conjunction with other physical data to extrapolate the shift in zones of intertidal biota. Along dynamic sedimentary shore lines such as beaches, mudflats and salt marsh, sediment stability will be examined in order to predict changes in shore line configuration (estimated cost: $700,000; duration: 4 years).

e. An examination of the degree to which the primary production of organic food matter by phytoplankton will be altered by increased tidal mixing. The growth of phytoplankton provides much or all the energy (food) which drives all biological systems in coastal and offshore regions. This primary production of food matter by phytoplankton is profoundly influenced by water movements which are induced by tidal action. Much of the summer phytoplankton production occurs in tidally well-mixed areas and along frontal regions between thermally stratified and non-stratified water masses. Increased tidal amplitude would increase the intensity of vertical mixing and expand the area over which more vigorous mixing occurs. Greater tidal currents could also extend and displace the formation of productive frontal regions. Increased mixing could, however, under some situations, reduce phytoplankton growth by mixing phytoplankton to greater depths away from light.

Phytoplankton production may be examined over spring-neap tidal cycles using research vessels to examine water column structure and primary production. Imagery from satellites and low-flying aircraft would provide large scale data on vertical

mixing, water temperature, circulation patterns and phytoplankton abundance. These remote data on surface waters would also be of great use to many other studies where logistical scales would prevent the use of other traditional, ground level methodologies. This effort will be complemented by both 1) the examination of other factors which influence vertical mixing, e.g. wind stress, and 2) the investigation of light, temperature, nutrient variability, water history and zooplankton grazing which control patterns of productivity (estimated cost: $1,000,000; study duration, 4 years).

f. The determination of physical and biological estuarine responses resulting from increased vertical mixing and flushing. Increased tidal flushing of estuaries will occur in estuaries. These events may disperse pollutants faster and increase primary productivity of organic food matter. To what degree will flushing and vertical mixing be changed in various estuaries and how will the systems respond in terms of temperature, salinity, productivity, pollution assimilation and community distribution? Field work should be included to identify sensitive areas where basic biological alterations may occur.

Remote sensing imagery from low-flying aircraft could be used to collect synoptic high resolution data on water temperature, vertical mixing, front formation, circulation patterns, sediment load, macrophyte abundance, phytoplankton abundance, and shore line structure in coastal and estuarine regions. These data would be of great use to other research

efforts and could serve as an important coastal link with tidal model predictions in open waters. If obtained over spring-neap tidal cycles, this information would be of great predictive value and could be obtained by no other means over such a large and complex coastal region.

Remote data would be complemented by hydrographic and biological studies of water column structure and productivity. Productive benthic plant and animal populations will also be assessed to determine potential tidal effects (estimated cost: $500,000; study duration: 4 years).

g. <u>Case studies of socio-economic impacts to develop deeper insight needed for planning detailed investigations</u>. While many potential economic impacts can be identified at this time others may also exist. Case studies in two or three coastal communities should be made by a multi-disciplinary team to develop a deeper understanding of the economic consequences to various sectors of the community. This would allow for the formulation of a detailed plan for socio-economic studies. The product of this investigation would be an assessment of local socio-economic impacts and a detailed plan for their study (estimated cost: $200,000; study duration: 1 year).

h. <u>An examination of tidal predictions in the context of naturally rising sea level and expanding tidal range</u>. Both mean sea level and tidal range are naturally increasing in the Gulf of Maine. The tidal perturbations caused by Fundy tidal power development and their environmental consequences, need

to be evaluated in the context of this rapidly rising sea level and expanding tidal range.

Global rises in sea level, alarming rates of coastal subsidence observed for some coastal areas of Maine, and a naturally increasing tidal range represent long-term environmental threats for which planning is needed. Flooding and impacts resulting from this flooding will be greatly accelerated by a 15 cm rise in mean high water due to tidal power construction in Minas Basin. All factors which produce changes in mean sea level and tidal range should be quantified in detail along the Maine coast. The ways in which alterations of mean sea level and tidal range are similar and dissimilar should be closely evaluated (estimated cost: $250,000; study duration: 2 years).

i. <u>The influence of a tidal power dam in Minas Basin on migratory fish populations along the U.S. coast</u>. The American shad and possibly other finfish whose migratory patterns normally lead them into Minas Basin may be adversely influenced by the presence of a tidal dam. The influence of this migratory disruption and the degree to which larger fish may be injured by tidal power turbines must be evaluated.

The extent to which these potentially damaged populations represent a large or significant proportion of fish caught along the U.S. Atlantic coast should be considered. The tagging and recapture of major migratory species such as American shad, blueback herring, Atlantic salmon, striped bass, Atlantic sturgeon, dogfish and large sharks should be

conducted together with an analysis of potential effects of migratory interruption and damage by turbines (estimated cost: $250,000; study duration, 3 years).

2. MEDIUM PRIORITY RESEARCH NEEDS

a. The influence of dam design and operation on storm surges. The ways in which dam construction and operation may lessen tidal enhancement during storm surges should be examined. The suggestion has been made that opening the dam would increase its permeability and reduce tidal ranges. Speculation has also arisen that the operation of the tidal power facility out of phase with the existing tidal regime may further dampen the tides. If correct, such actions might lessen potential flood damage from storm tides. The Greenberg model, however, suggests that several tidal cycles would be required to achieve tidal dampening after the dam were made more permeable. This would preclude the effectiveness of the aforementioned efforts to attain tidal dampening in that dam operators would have to know of storm surges a few days in advance of their occurrence in order that the dams could be opened. Such storm surge predictions are not possible.

It is necessary to calculate the degree to which dam opening and phase operation may reduce tidal tides. It is also important to determine the length of time such actions would take to produce significant reductions in these ranges.

b. Regulation of dam operation to lessen unanticipated deleterious effects. If unacceptable environmental influences are produced by a long-term alteration of tidal regimes, could routine plant operation be changed to decrease tidal effects and would tidal power management be willing to alter its operation? While it is clear that many potential problems resulting from an altered tidal regime can be identified, only some predictions may be quantified before operation begins. It is also quite probable that some unexpected deleterious influences may result, some of which may be significant. Possible mechanisms which could reduce tidal range should be explored in addition to the willingness of management to implement them.

c. Predicted rates of tidal change due to dam construction. The rate at which a 30 cm increase in tidal range is achieved has considerable importance. Rates of tidal change will be a function of how quickly dam construction changes the tidal basin period. Once specific construction plans are finalized, the rate of dam construction needs to be evaluated and rates of tidal change calculated.

d. An examination of water temperature changes and their climatic influences. As a result of accelerated vertical mixing, surface water temperatures may be decreased in summer. How much will they be decreased, over what areal extent and over what period? Once these issues are resolved air-sea interactions should be examined to determine the magnitude of climate changes along the coastal zone.

e. <u>Damage to coastal structures</u>. Greater storm damage will occur if storm tides coincide with periods of elevated high water due to tidal power development. What types of storm damage are likely to be expanded and what will be their monetary costs? Many structures are located near high water levels and may be damaged by an elevation of mean high water and storm tides. Roads, bridges, railways, utilities, seasonal and year round homes, which would be influenced must be identified. Based on case study results and using flood plain maps and site visits, it would be possible to identify threatened structures.

f. <u>Physical and biological consequences of natural tidal variability</u>. The physical and biological consequences of the existing natural variability in tidal cycles should be examined. A natural change in tidal current strength is associated with the 19 year tidal cycle. This is believed to influence fishery landings. Estuarine areas of similar morphology but differing in tidal range could be compared to evaluate the tidal influences. The data base and computer programs exist for these comparisons. These comparisons will allow quantitative estimates to be made of the biological consequences of the projected tidal regime alterations.

g. <u>Salt water intrusion into groundwater</u>. Salt water intrusion to groundwater wells is likely to be exacerbated. How widespread would this effect be and what costs would be incurred?

h. The physical and biological consequences of power plant closure. Tidal power facilities may be long lived, but may someday be closed. If tidal dams are dismantled or made more permeable, a decrease in tidal amplitude may be experienced. Physical and biological regimes, as in salt marshes, which will have adjusted to greater tidal amplitudes could be disrupted by a decrease in tidal amplitude. Such events need consideration.

C. INTEGRATED RESEARCH PLAN

The interrelated nature of many basic problems associated with tidal range alteration suggests that these may be best approached in a single, integrated program of research. Generally speaking we need to improve our understanding of the ways in which the physical regime will be changed. We need to know with greater precision how an expanded tidal range will be translated into alteration of current velocity, turbulence, vertical mixing and surface temperature. Over how large an area will these influences be felt? Such information is needed to predict many physical and biological consequences. Only when these needs are met can many socio-economic predictions be made.

A detailed integrated research plan has been assembled at the Bigelow Laboratory for Ocean Sciences and is available upon request. In summary, this integrated plan has components which consider (1) confirmation of tidal predictions, (2) selected scientific investigations, (3) workshops, (4) agencies to guide support and evaluate studies, (5) time schedules, and (6) program costs.

1. SCIENTIFIC EFFORTS

The selected scientific investigations include analysis of shoreline and bottom alterations, shoreline ecosystems, estuarine ecosystem and offshore ecosystems. These efforts, together with the confirmation of tidal predictions, are similar to those previously described under "Individual Research Plans."

2. WORKSHOPS

It is suggested that workshops be sponsored to allow scientists, supporting agencies and other interested parties to exchange ideas and follow scientific progress. Scientific efforts will clearly involve a great number of diverse but interrelated studies. It is essential that all investigators periodically organize their data for presentation to colleagues within the program as well as other scientists. This will also serve in the critical evaluation of scientific programs.

We envision the need for 5 three-day workshops where all program scientists will participate. These workshops will supplement the more frequent assembly of groups of scientists who are collaborating closely.

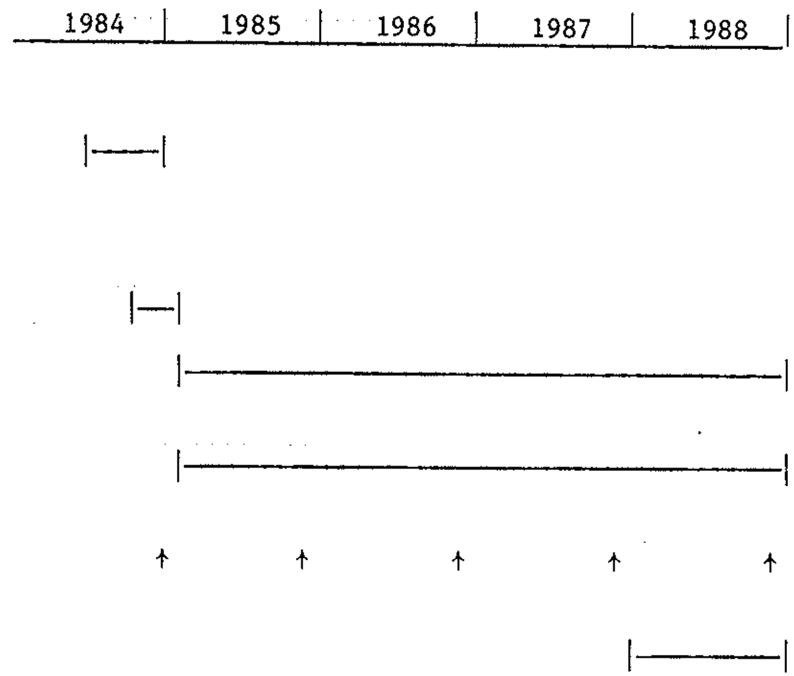
3. AGENCIES TO GUIDE, SUPPORT AND EVALUATE SCIENTIFIC STUDIES

It is of critical importance that all scientific efforts be well planned, adequately supported and critically evaluated. We suggest that an oversight committee be established to organize and supervise the scientific research.

Since it is clear that both Canada and the U.S. will have an interest in this project it is appropriate to develop such a committee with U.S. and Canadian representation, including members from properly

mandated Federal, State and provincial environmental and regulatory agencies, academic and private sectors. This sort of broad oversight will ensure quality in timely, comprehensive studies that will provide meaningful scientific input to the decision making process.

4. TIME SCHEDULE



1. Organization of agencies to guide and support research

2. Evaluation of tidal model

   A. Commentary by oceanographers

   B. Extension of model

3. Selected investigations

4. Workshops

5. Preparation of final reports

5. INTEGRATED PROGRAM COSTS

	Duration	Cost	Total Cost
1. Evaluation of tidal model by oceanographers	4 mo	$7,000/mo	$28,000
2. Extension of tidal model	4 yr	$200,000/yr	800,000
3. Selected investigations			
A. Shore line and bottom studies	4 yr	240,000/yr	960,000
B. Shore line ecosystems	4 yr	220,000/yr	880,000
C. Estuarine ecosystems	4 yr	190,000/yr	760,000
D. Offshore ecosystems	4 yr	280,000/yr	1,120,000
4. Workshops	5 workshops	30,000 each	150,000
TOTAL COST			$4,698,000

BIBLIOGRAPHY

Allison, H. 1980. Enigma of the Bruun's formula in shore erosion. Proc. Per Bruun Symposium, Newport, RI, Nov. 1979, p. 67-78.

Anderson, F.E. 1972. Resuspension of estuarine sediment by small amplitude waves. J. Sed. Petrol. 12: 602-607.

Anderson, F.E. 1976. Rapid settling rates observed in sediments resuspended by boat waves over a tidal flat. Neth. Sea Res. 10: 44-58.

Anderson, F.E., L. Black, L.E. Watling, W. Mook and L.M. Mayer. 1981. A temporal and spatial study of mudflat erosion and deposition. J. Sed. Petrol. 51: 726-736.

Anderson, M. and Wall, D. 1978. Potential importance of benthic cysts of Gonyaulax tamarensis and G. excavata in initiation of toxic dinoflagellate blooms. J. Phycol. 14: 224-234.

ATTPPB. 1969. Feasibility of tidal power development in the Bay of Fundy. Govts. of Canada, New Brunswick and Nova Scotia.

Baille, P.W. and B.L. Welsh. 1980. The effect of tidal resuspension on the distribution of intertidal epipetic algae in an estuary. Est. Coast. Mar. Sci. 10: 165-180.

Biggs, R.B. 1970. Sources and distribution of suspended sediment in northern Chesapeake Bay. Mar. Geol. 9: 187-201.

Bruun, P. 1962. Sea level rise as a cause of shore erosion. J. Waterways Harbors Div., Proc. Am. Soc. Civ. Eng. 88: 117-130.

Bruun, P. 1980. The "Bruun Rule": Discussion on boundary conditions. Proc. Per Bruun Symposium, Newport, RI, Nov. 1979, p. 79-83.

Caswell, W.B. and S. Ludwig. 1978. Maine coastal area water supply and demand. Maine Geol. Survey, Dept. Conservation, Augusta, Maine.

Daiber, F.C. 1977. Salt-march animals: distribution related to tidal flooding, salinity and vegetation. In Chapman. V.J. (ed.), Wet Coastal Ecosystems. Elsevier Scientific Publ. Co., New York, 79-108.

Dale, B., C.M. Yentsch and J.W. Hurst. 1978. Toxicity in resting cysts of the red-tide dinoflagellate Gonyaulax excavata from deeper water coastal sediments. Science 201: 1223-1224.

Dean, R.G. and T.L. Walton. 1975. Sediment transport processes in the vicinity of inlets with special reference to sand trapping. Proc. Estuarine Res. Fed. Conference, Myrtle Beach, SC. p. 129-150.

Dubois, R.N. 1975. Support and refinement of the Bruun Rule on beach erosion. J Geology 83: 651-657.

Dubois, R.N. 1976. Nearshore evidence in support of the Bruun Rule on shore erosion. J. Geology 84: 485-491.

Dubois, R.N. 1977. Predicting beach erosion as a function of rising water level. J. Geology 85: 470-476.

Duff, G.F.D. 1970. Tidal resonance and tidal barriers in the Bay of Fundy system. J. Fish. Res. Bd. Can. 27: 1701-1728.

Dyer, K.R. 1973. Estuaries: A Physical Introduction. John Wiley and Sons, London. 140 p.

Emery, K.O. and E. Uchupi. 1972. Western North Atlantic Ocean. Memoir 17, Am. Assoc. Pet. Geol., Tulsa, Oklahoma. 532 p.

Escoffier, F.F. 1977. Hydraulics and stability of tidal inlets. GITI Report #13, U.S. Army Coastal Engineering Research Center, 72 p.

Fundy Tidal Power Review Board. 1977. Reassessment of Fundy Tidal Power. 516 p.

Garrett, C.J.R. 1972. Tidal resonance in the Bay of Fundy and Gulf of Maine. Nature 238: 441-443.

Garrett, C.J.R. 1974. Normal resonance in the Bay of Fundy and Gulf of Maine. Can. J. Earth Sci. 11: 549-556.

Garrett, C.J.R. 1977. Tidal influence on the physical oceanography of the Bay of Fundy and Gulf of Maine. In Daborn, G.R. (ed.), Fundy Tidal Power and the Environment. Acadia Univ. Inst. 28: 101-105.

Garrett, C.J.R., J.R. Keeley and D.A. Greenberg. 1978. Tidal mixing versus thermal stratification in the Bay of Fundy and the Gulf of Maine. Atmosphere-Ocean 16: 403-423.

Gordon, D.C. and A.R. Longhurst. 1979. The environmental aspects of a tidal power project in the upper reaches of the Bay of Fundy. Mar. Pollut. Bull. 10: 38-45.

Gordon, D.C. and C. Desplanque. 1982. Dynamics and environmental effects of ice in the Cumberland Basin of the Bay of Fundy. Can. J. Fish. Aquat. Sci. (in review).

Gordon, D.C. and C. Desplanque. 1982. Ice dynamics in the Chignecto Bay Region of the Bay of Fundy. Can. J. Fish. Aquat. Sci. (in review).

Greenberg, D.A. 1969. Modification of the M_2 tide due to barriers in the Bay of Fundy. J. Fish. Res. Bd. Can. 26: 2775-2783.

Greenberg, D.A. 1975. Mathematical studies of tidal behavior in the Bay of Fundy. Ph.D. Thesis, Univ. Liverpool. 139 p.

Greenberg, D.A. 1976. Mathematical description of the Bay of Fundy-Gulf of Maine numerical model. Tech. Note. No. 16, Marine Environm. Data Service, Environm. Canada, Ottawa.

Greenberg, D.A. 1977. Mathematical studies of tidal behavior in the Bay of Fundy. Man. Rep. Ser. No. 46, Marine Sciences Directorate, Dept. Environm., Ottawa.

Greenberg, D.A. 1979. A numerical model investigation of tidal phenomena in the Bay of Fundy and Gulf of Maine. Mar. Geodesy 2: 161-187.

Hands, E.B. 1977. Implications of submergence for coastal engineers. Coastal Sediments '77 Proc., Fifth Symposium of the Waterways, Ports, Coastal and Ocean Div. of A.S.C.E., p. 149-166.

Harrison, E.Z. and Bloom, A.L. 1977. Sedimentation rates on tidal salt marshes in Connecticut. J. Sed. Petrol. 47: 1484-1490.

Hicks, S.D. 1972. On the classification and trends of long period sea level rises. Shore and Beach, pp. 20-23.

Hicks, S.D. 1978. An average geopotential sea level series for the United States. J. Geophys. Res. 83: 1377-1379.

Hoffman, J.S., D. Keys and J. Titus. 1983. Projecting sea level rise. Methodology, estimates to the year 2100 and research needs. EPA 230-09-007, 121 pp.

Jackson, J.R. 1973. A model study of the effects of small amplitude waves on resuspension of fine-grained cohesive sediments. M.S. Thesis, Univ. New Hampshire, Durham. 52 pp.

Jarrett, J.T. 1976. Tide prism-inlet relationships. GITI Report 3, U.S. Army Coastal Engineering Research Center. 32 pp.

Knight, R.J. and R.W. Dalrymple. 1976. Winter conditions in a macrotidal environment, Cobequid Bay, Nova Scotia. Rev. Geograph. Montreal 30: 65-85.

Larsen, P.F. and L.F. Doggett. 1979. The salinity and temperature distributions of selected Maine estuaries. Maine State Planning Office, Augusta, Maine. 110 p.

Larsen, P.F. and L.F. Doggett. 1981. The ecology of Maine's intertidal habitats. Maine State Planning Office, Augusta, Maine. 183 pp.

Lewis, C.M., Yentsch, C.M. and Dale, B. 1979. Distribution of Gonyaulax excavata resting cysts in the sediments of the Gulf of Maine. In Taylor, D.L. and Seliger, H.H. (eds.), Toxic Dinoflagellate Blooms, Elsevier, North Holland, 235-238.

Mandelbrot, B.B. 1977. Fractals. W.H. Freeman and Company, San Francisco. 365 p.

Nelson, B.W. and L.K. Fink. 1978. Geological and botanical features of sand beach systems in Maine. Maine State Planning Office, Augusta, Maine. 269 pp.

Newbury, R.W. and G.K. McCullough. 1982. Shoreline erosion and restabilization in the Southern Indian Lake reservoir. Can. J. Fish. Aquat. Sci. (in review).

Nixon, S.W. 1980. Between coastal marshes and coastal waters - a review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. In Hamilton, P. and MacDonald, K.B. (ed.), Estuarine and Wetland Processes. Plenum, New York, 437-525.

Nixon, S.W. 1982. The Ecology of New England High Salt Marshes: a community profile. Biological Services Program, Washington, D.C. FWS/OBS-81/55.

O'Brian, M.P. 1931. Estuary tidal prism related to entrance areas. Civil Eng. 1: 738-739.

O'Brian, M.P. 1966. Equilibrium flow areas of tidal inlets on sandy coasts. Proc. 10th Ann. Coastal Eng. Conf. 1: 676-686.

Permanent Service for Mean Sea Level. 1977. Monthly and annual mean heights of sea level, Vol. 2., Inst. Oceanogr. Sci., Bidston Observatory, Birkenhead, Merseyside L43 7RA, England.

Pingree, R.D., P.M. Holligan and G.J. Mandell. 1978. The effects of vertical stability on phytoplankton distribution in the summer on the northwest European Shelf. Deep-Sea Res. 25: 1011-1028.

Proudman, J. 1953. Dynamical Oceanography. Methuen and Co., London. 409 pp.

Rao, D. 1968. Natural oscillations in the Bay of Fundy. J. Fish. Res. Bd. Can. 25: 1907-1114.

Reid, P.C. 1980. Toxic dinoflagellates and tidal power generation in the Bay of Fundy, Canada. Mar. Poll. Bull. 11: 47-51.

Reineck, H.E. 1967. Layered sediments of tidal flats, beaches, and shelf bottoms of the North Sea. p. 191-206. In G.H. Lauff (ed.) Estuaries, pub. #83. Amer. Assoc. Adv. Sci. Washington, D.C. 757 pp.

Rosen, S. 1978. A regional test of the Bruun Rule on shoreline erosion. Mar. Geology 26: M7-M16.

Rudolph, R.W. and P.F. Larsen. 1983. Transnational legal issues and Fundy tidal power. Proc. Coastal Zone 1983. (in press).

Schwartz, M.L. 1965. Laboratory study of sea level rise as a cause of shore erosion. J. Geology 73: 528-534.

Schwartz, M.L. 1967. The Bruun theory of sea level rise as a cause of shore erosion. J. Geology 75: 76-92.

Seliger, H.H., M.A. Tyler and K.R. McKinley. 1979. Phytoplankton distributions and red tides resulting from frontal circulation patterns. In Taylor, D.L. and Seliger, H.H. (eds.), Toxic Dinoflagellate Blooms, Elsevier, North Holland, 249-256.

Simpson, J.H. and Hunter, D.R. 1974. Fronts in the Irish Sea. Nature 250: 404-416.

Stone and Webster Engineering Corp. 1978. Determination of coastal storm tide levels. Federal Insurance Administration, U.S. Dept. Housing and Urban Develop., Washington, D.C.

Thompson, C.I. 1977. The role of ice as an agent of erosion and deposition on an estuarine tidal flat. M.S. Thesis, Univ. New Hampshire, Durham. 64 pp.

Tidal Power Corporation. 1982. Fundy tidal power update '82. Halifax, Nova Scotia.

Topinka, J.A. and Korjeff, W.A. 1981. Benthic macrophyte programs: Evaluation of Maine shoreline. In Bigelow Laboratory for Ocean Sciences Annual Report, 1980-1981, 33 pp.

Topinka, J.A., L. Tucker and W. Korjeff. 1981. The distribution of fucoid macroalgal biomass along central coastal Maine. Bot. Mar. 24: 311-319.

Tyler

U.S. Army Corps of Engineers, New England Division. 1979. Blizzard of 1978, coastal storm damage study, Waltham, Massachusetts.

Weggel, J.R. 1979. A method for estimating long-term erosion rates from a long-term rise in water level. Tech. Aid No. 79-2, U.S. Army Corps Eng., Coastal Eng. Res. Ctr., Ft. Belvoir, VA. 16 p.

Yentsch, C.M. and F.C. Mague. 1979. Motile cells and cysts: Two probable mechanisms of intoxification of shellfish in New England waters. In Taylor, D.L. and Seliger, H.H. (eds.), Toxic Dinoflagellate Blooms, Elsevier, North Holland, 127-130.

Yentsch, C.S. and N. Garfield. 1981. Principal areas of vertical mixing in the waters of the Gulf of Maine with reference to total productivity of the area. In Gower, V.F.R. (ed.), Oceanography from Space, Plenum Publ. Corp., New York pp. 303-312.

Appendix I. Written comments on Greenberg model

Bigelow
Laboratory
For
Ocean
Sciences
A DIVISION OF NORTHEASTERN RESEARCH FOUNDATION, INC.

24 August 1982

Dr. H.G. Tolland
Energy Technology Support Unit
Building 156
AERE Harwell
Oxfordshire OX11 ORA
UNITED KINGDOM

Dear Dr. Tolland,

The Bigelow Laboratory has recently been commissioned by the Maine State Planning Office to do a preliminary environmental assessment of the potential impacts of Fundy tidal power development on the resources of the State of Maine. While the principal thrust of our investigation will be ecological and socio-economic in nature, the reliability of the numerical modelling of the Gulf of Maine tidal system, and its modification by the proposed project will have a bearing on all aspects of our work. Mr. George Baker of the Nova Scotia Tidal Power Corporation has given us your name as someone with sufficient knowledge to comment.

As you are aware, Dr. David Greenberg of the Bedford Institute of Oceanography has produced a numerical tidal model which predicts that construction of the Minas Basin tidal barrage will increase the tidal range in the western Gulf of Maine by 30 cm (Greenberg, D.A., 1979, A Numerical Model Investigation of Tidal Phenomena in the Bay of Fundy and Gulf of Maine. Marine Geodesy 2: 161-187.). We are using these predictions for our projections of the ecological consequences but would appreciate your expert opinion on their reliability so we can portray the potential impacts with realistic confidence intervals. Specifically, do you believe the model is correct in predicting enhanced tidal resonance in the Bay of Fundy-Gulf of Maine system? Are the magnitudes of projected tidal range increase reasonable? How reliable are the projections at the model's boundaries? What could be done to improve the projections, if necessary?

Many laypeople have difficulty accepting the tidal predictions and call for a second, independent modelling effort. Many oceanographers, on the other hand, are satisfied with the way the model fits the existing conditions and believe further modelling is not necessary. Do you

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believe that it would be beneficial for U.S. interests to independently model the system and, if so, how much would it cost and how long will it take?

A major environmental concern is the impact of storm surges on top of the higher tidal levels. There has been discussion that it may be possible to dampen the effects of storm surges by opening all the turbines and sluice gates and thereby mitigate the impacts. From your experience do you believe that a tidal system the size of the Gulf of Maine could respond quickly enough that storm surge damage could be mitigated in this way?

Your comments on these questions will help us greatly in our efforts and will help to define future research needs should the Fundy project continue to develop.

Thank you very much for your consideration.

Sincerely yours,

Peter F. Larsen

Peter F. Larsen, Ph.D.
Senior Research Scientist

PFL:po

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Date 20 September 1982

Dr P F Lawson
Senior Research Scientist
Bigelow Laboratory for Ocean Sciences
McKown Point
West Boothbay Harbour
Maine 04575
USA

Dear Dr Lawson

FUNDY TIDAL POWER - NUMERICAL MODELLING

Some of the questions which you raise in your letter of 24 August concerning Mr Greenberg's model are similar to those which concerned us at the outset of the Severn Tidal Power studies. Like you, we used the results of the models in assisting us with various impact studies.

Our studies made use of models developed at the Institute of Oceanographic Sciences and the Hydraulics Research Station. There was close integration of the work of the two groups of modellers, with IOS concentrating on remote effects and the impact of any tidal range alteration on energy output and HRS concentrating on the flow patterns in the estuary. HRS relied on IOS predictions of remote effects. The models were fundamentally the same in terms of the governing equations and the manner of solving them. The Greenberg model is similar to the IOS model, indeed he started work on it while at IOS.

I have consulted with oceanographers at IOS and HRS to seek their views on the Greenberg model. Their views confirm those of the oceanographers you mention; they are satisfied with the way that the model fits the existing conditions and believe further modelling is not necessary. The Fundy system has now been studied in great detail, probably rather more than in the Severn. Boundary conditions now take account of the effects of the Atlantic Ocean, the model itself going out to the edge of the shelf. The process of validation both at the coast and shelf edge for Fundy gives confidence that the model has homed in the right behaviour. All this amounts to a pretty thorough investigation.

It is accepted that the enhanced resonance is correct and that the model is close to the right anser in magnitude. The accuracy of the model tides is probably correct to within a few percent in amplitude and the phases are quite good. Dr Greenberg no doubt has a good idea of the probable accuracy and could advise you on confidence limits.

Neither I, nor the oceanographers I have spoken to, believe that it is necessary to develop an independent model. It would probably be better to have the Greenberg model examined by an independent export if you believe there are sufficient doubts to warrent this. To develop an adequate model from scratch would take one to two years with costs in the region of £100,000 (based on commercial rates in the UK). If you are able to use a pre-existing model then it might only be necessary to insert the Fundy geometry, and then calibrate.

Mr P F Lawson

20 September 1982

This could take around three months. After model development, test runs could be carried out at the rate of one to two tests a month, depending on the complexity of the test.

I can only give a qualitative answer to your question concerning storm surges. The resultant tidal amplitude is made up of the incoming tidal wave and the reflected wave from the barrage. The expected increase in tidal amplitude is ude to the reflection from the barrage and any modification of the barrage by, say, leaving all sluices and turbines open would modify this reflected wave and lead to a rapid response. There are however two problems:

- to kill off the reflected wave entirely would mean removing the barrage: opening all sluices and turbiens would only knock out part of the reflection, ie reduce but not eliminate the enhanced tidal range.

- the influence of the barrage travels at a velocity of $\sqrt{gd}$ where d is an average depth. This suggests that it would probably be some hours for it to get say several hundred km to the areas of concern to you.

The response of the system could be readily modelled and it may well be worth your commissioning Dr Greenberg to carry out a suitable study.

Finally, I would anticipate changes in the patterns of water movement and sedimentation could well be important to your environmental impact studies. This is certainly the case for our Severn Studies. The 30 cm change of tidal range implies relatively modest changes in velocity. However, sediment transport depends on a high power of velocity, something like the fourth power. Also, the shape of the tide curve will change. Both these factors suggest a change in the nett sediment movement. I understand Dr Greenberg has carried out work on sedimentation changes and this could be worth following up.

I hope these remarks are useful to you. However, if you want further technical information it could be useful to contact Dr Norman Heaps at the Institute of Oceanographic Sciences, Bidston Observatory, Birkenhead L43 7RA, England. Dr Heaps lead the modelling effort at IOD on the Severn and is familiar with Dr Greenberg's work.

Yours sincerely

W A Danby

pp H G TOLLAND
Tidal Power Group

Rand
SANTA MONICA, CA. 90406

15 September 1982

Dr. Peter F. Larsen
Senior Research Scientist
Bigelow Laboratory for Ocean Sciences
McKown Point
West Boothbay Harbor ME 04575

Dear Dr. Larsen:

In your letter of August 24, 1982 you asked many questions concerning the modeling of the Gulf of Maine and the Bay of Fundy which are not easy for me to answer as I am not familiar with the studies performed up-to-now.

My first reaction is that it would have been very difficult to obtain a study of this quality in the United States for reasons which I will explain later.

I have reservations, however, which do not reflect on the work done by Dr. Greenberg. I feel he has been working from an insufficient data base. In my opinion, accurate tide data should be measured at the model boundaries simultaneously with currents in the Gulf and Bay and vertical tides at the significant shore stations. Only when this is done can an actual simulation of the water movements be made as a verification of the model and more insight in the boundary problem can then be obtained.

Dr. Greenberg used navigation charts to describe the bathymetry. This is not accurate. In the modeling investigations for the Netherlands Rijkswaterstaat, we found it necessary to use depth surveys taken at about the same time as the tide data to obtain good results.

The increase in tidal range for Boston, as described in Marine Geodesy for one of the barrier schemes, is larger than I would expect but this increase is still about the same as the accuracy of the computations and, for this reason, more accuracy would be required to find its significance.

Your question as to a separate modeling effort is, in my opinion, dependent upon the potential impact the estimated changes in the regime may have, and, naturally, the possibility that the plan will be executed. If these impacts are considerable then you need to extend the work, but this would only be beneficial if better tide data is available as outlined above.

The cost of such a modeling study is high--my rough estimate would be $1,500,000 to $2,000,000 over a four year period, and this would not include the field work. An engineering study would be required. As you indicate in your letter,

oceanographers are generally satisfied when the phenomena are well represented. In engineering studies this is not the case and we have to work much more accurately.

In the beginning of my letter I indicated that it would be difficult to duplicate the study in the United States. Modeling is an art and a science. The art has to be learned and requires experience. Dr. Greenberg was fortunate to have studied and worked in England with one of the most experienced groups in tidal computations. In my own career I have benefitted enormously through my association with the Deltadienst of the Netherlands Rijkswaterstaat.

In the United States the main tool in estuary studies has been physical models and no pioneering work was done to develop the mathematical modeling technology by the responsible agency. A recent overview of present capabilities in the U.S. can be found by reviewing the Proceedings of the First Two-Dimensional Flow Modeling Seminar at the Hydrologic Engineering Center, Davis, California (U.S. Army, Corps of Engineers, March 1982).

As far as reducing tidal height during storms by opening sluice gates, this cannot be answered quickly. Some engineering calculations and simulations would be required and if a model is available then this can be quickly resolved. It should be realized that the operator of the facility would be reluctant to take these steps as loss of energy would be involved and an extensive Operations Research project would be required to set guidelines for operation. For the storm surge barrier in the Delta region of the Netherlands our Corporation had a large research project for several years in which engineers of the Delta Service participated to determine when the gates should be closed.

The varying depth and non-linear effects cause the tide to generate residual currents and this was not discussed by Dr. Greenberg. These residual currents are often important for the ecosystem.

For your information I am enclosing two reports and a paper which may be of interest to you.

Sincerely yours,

J Leendertse

Jan J. Leendertse
Engineering and Applied Sciences
Department

JJL:gc

Enclosures: 1. Reprint: *Two-Dimensional Tidal Models for the Delta Works*
2. R-2121/1-NETH
3. R-2444/1-NETH

Woods Hole Oceanographic Institution
Woods Hole, MA 02543
Phone: (617) 548-1400
Telex: 951679

15 October 1982

Dr. Peter F. Larsen, Senior Research Scientist
Bigelow Laboratory for Ocean Sciences
McKown Point, West Boothbay Harbor, ME 04575

Dear Dr. Larsen:

In answer to your questions concerning barrier-induced tidal system modifications in the Gulf of Maine, I enclose the following comments and assessments.

Dr. Greenberg is a mature and thoughtful scientist; his tidal model for the Gulf of Maine/Bay of Fundy system, while in some respects not "state-of-the-art", has been carefully constructed and shown to approximately reproduce the available tidal observations in this region. I am unaware of any more thorough study of this tidal modification problem than that summarized in Dr. Greenberg's recent papers and reports. In general, therefore, I believe that his qualitative predictions of enhanced tidal resonance are likely correct.

Nonetheless, in view of certain unresolved physical as well as computational issues (such as sensitivity to improvements in model geometry, topography, boundary condition implementation, parameterization of flooding/covering of tidal flats, etc.), I would suggest that the present quantitative predictions of tidal enhancement be treated with caution. In particular, it is difficult to assess the reliability of Greenberg's enhancement figure of 30 cm for the western Gulf of Maine in the absence of prior examination of the above-mentioned issues.

It is technically feasible to construct a tidal model for the Gulf of Maine/Bay of Fundy system with several improvements over existing models - including irregular grid finite-difference or finite-element techniques offering a more accurate representation of coastal boundaries, and improvements in open ocean boundary condition specification and model resolution. Since such a model might be expected to reproduce the qualitative features of Dr. Greenberg's results, its development would only be warranted if improved quantitative predictions of tidal enhancement were required. (This, in turn, depends upon the predictive skill required for management decisions.) The development and utilization by U.S. interests of an independent tidal modelling activity would cost (very roughly) $150,000-250,000, take (equally roughly) two years, and require several half-to-full-time theoretical oceanographers/data processors/programmers.

It may be possible, as you suggest, to partially control the effects and impact of storm surge damage by opening all turbines/sluice gates. The efficacy of such an approach would crucially depend, in turn, on the

predictive ability of operational coupled meteorological/storm surge models for the Gulf of Maine region. Given reasonable advance notice of a coming surge, say about 12 hours, corrective action might be taken. This level of predictive skill for surges is presently attainable, but might also require model development of a sort similar to that discussed above.

If I may be of further help, please let me know.

Yours sincerely,

Dale B. Haidvogel

Dale B. Haidvogel
Associate Scientist

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