The influence of increased tidal amplitude on the physical biological and chemical regimes of the Gulf of Maine

by

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This report considers specific topics which are of relevance to the construction of the tidal power barrage in the Minas Basin, Bay of Fundy. This work constitutes a major input into the report to the State of Maine State Planning Office to evaluate barrage influences on the State of Maine and the Gulf of Maine.

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.

Primary plant production

Despite the importance of primary production, total levels of production for the Gulf of Maine and its coastal waters are inadequately known. Many of the factors that control this growth are also poorly understood. It is therefore not possible to prepare an accurate carbon, or food budget for the plant contribution to the Gulf of Maine. It is therefore also not possible to confidently predict the absolute amount of organic food matter that will be gained or lost as a result of a given change in tidal amplitude. It is possible, however, to estimate the gross orders of primary production of some of the major marine plant communities and comment on some of the alterations that might be induced by a change in tidal regime.

The gross order of primary production for most of marine plants may be estimated by multiplying together plant density, carbon production or growth rates and the area over which the plants are found. Yentsch and Garfield (1981) estimated the total area of the Gulf of Maine region to be 1.40×10^5 Km^2. This region includes the central portion of the Gulf of Maine and Georges Bank to the 100 m isobath. In this area estimate, the Bay of Fundy, St. Mary's Bay and Nantucket Shoals are excluded. Simulated *in situ* incubations using the ^{14}C technique to determine phytoplankton productivity have suggested that annual phytoplankton production in the Gulf of Maine proper is on the order of 415 g $C \cdot m^{-2} \cdot yr^{-1}$, while production over Georges Bank is 655 g $C \cdot m^{-2} \cdot yr^{-1}$ (O'Reilly and Evans, 1981). Assuming an average productivity of 500 g $C \cdot m^{-2} \cdot yr^{-1}$ for the phytoplankton of the entire Gulf of Maine region, and multiplying by an area roughly 1.40×10^5 Km^2 yields a large productivity of 7000×10^4 metric tons of $Carbon \cdot yr^{-1}$.

The major intertidal algae of rocky shores, *Ascophyllum nodosum* and *Fucus* sp. occur at mean densities of 63.3 and 15.3 Kg wet wt•m of $shoreline^{-1}$ respectively (Topinka *et al.*, 1981). Over Maine's 6705 km of marine and estuarine shoreline (Topinka and Korjeff, 1981), assuming one biomass turnover per year, these plants produce approximately 4.5×10^4 metric tons $C \cdot yr^{-1}$. Where subtidal and intertidal macroalgal populations have been examined together (Mann, 1972 a,b) subtidal productivity may be approximately at least one order of magnitude higher than intertidal productions. If this is true, the subtidal macroalgae of the coast of Maine may produce $45. \times 10^4$ metric tons $C \cdot yr^{-1}$.

Emergent coastal marshes and estuarine phytoplankton populations over the coast of Maine between Canadian border and Cape Elizabeth have been examined (Topinka, 1980). Their productivities have been estimated at 1.9×10^4 and 4.2×10^4 metric tons $C \cdot yr^{-1}$ respectively.

In order to be strictly comparable to the offshore Gulf of Maine phytoplankton, area and productivity of coastal populations must ultimately take into account the total coastal boundaries. The border estimates given here for most of coastal Maine may be multiplied by a factor of approximately 3 to arrive at an approximate coastal boundary for the Gulf of Maine region. Having done this, however, makes little difference in the relative comparison of offshore Gulf of Maine phytoplankton and coastal populations, with offshore phytoplankton dominating production.

These gross estimates are only to offer a useful perspective on plant production of food in terms of C for the Gulf of Maine and its coastal waters. Firstly, it is obvious that the offshore phytoplankton populations inhabit large areas and to a large extent control productivity. Secondly, within coastal areas, intertidal macroalgae, subtidal macroalgae and emergent salt marsh plants all contribute large amounts of organic food in addition to that produced by estuarine phytoplankton. Thirdly, the production of relatively small coastal estuarine areas, support high and diverse plant production, which may be of great importance to coastal fisheries.

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 nutrient rich bottom waters to upper regions where phytoplankton need nutrients to grow.

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. Greenberg (1977) considered that the greater tidal amplitude derived from the Economy Point barrage could increase tidal currents by about 5% in the Gulf of Maine. Corresponding decreases in surface water temperature on the order of 1°C (Garrett, 1977) might result from enhanced, but not dramatically altered vertical mixing (Garrett *et al.*, 1978).

An increased mixing of the surface waters in summer would result in an increase in primary productivity due to an increase in nutrient supply despite the fact that phytoplankton would also be transported to greater depths and away from light. 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 observation demonstrate the relative importance of vertical mixing events in the primary production process.

Some, perhaps much, of this tidal energy may result, however, in the mixing of bottom waters and have a lesser influence on surface mixing (D. Greenberg, personal communication). Increased mixing of bottom water, however, would also be expected to enhance nutrient availability to phytoplankton to some extent. In this instance, higher current velocities and greater turbulence at the bottom could act to reduce nutrient concentrations at sediment surfaces resulting in steeper concentration gradients within the sediments. The effect could be an increased rate of nutrient diffusion from sediments. High bottom current velocities could also increase food availability to some bottom animals such as filter feeders. This would also increase rates of nutrient regeneration.

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 amplitudes 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." This degree of increased production is not likely to favor particular groups to any large extent, but may simply result in a slightly elevated animal production. This is in contrast to what is expected behind a large tidal barrage where major changes in primary producers are expected to result in major shifts in the abundance of consumer organisms (Gordon, 1982). While the magnitude of primary production increases in the Gulf of Maine region may not be dramatic, any small increase in this vital process may be significant.

While inshore waters occupy smaller horizontal areas, their high and diverse primary production and habitats support extensive, diverse and important populations of fauna. As previously mentioned, 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.

Increased nutrient supplies due to enhanced tidally induced vertical mixing could support greater phytoplankton growth where nutrients limit production. This stimulatory effect could be greatest in shallow estuaries where shallow sill depth prevents the input of large amounts of colder, nutrient-rich water. In estuaries, 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.

Magnitude of biological changes

A 10% increase in tidal amplitude 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 population 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 most species, however, the change in tidal regime will have no dramatic impact. In general, the character and abundance of biological populations would remain much the same. This is not, however, to say that biological regimes will be unaltered. A 10% increase in tidal amplitude will result in changes in current velocities, mixing processes and temperature gradients of primary production. These are among the major driving forces for biological populations and even subtle alterations are likely to be felt by many organisms.

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 upward long time upward 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.

Readjustment periods for biological populations

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

Before this equilibrium is reached, some populations will experience increased instability and stress. During this period, some biological populations will undergo some level of readjustment. This readjustment could be prolonged in some sedimentary habitats such as salt marshes where marsh levels are critical and slow to respond to an altered tidal regime. Salt marshes are generally considered to be areas of sediment accumulation where accretion of sediments and marsh levels often keep up with or surpass sea level rises caused by gradual land subsistence or glacier melting (Nixon, 1980). Marsh accretion rates in high marsh areas are those dominated by *Spartina patens* demonstrate accretion rates of 2.0-6.6 $mm \cdot yr^{-1}$ (Harrison and Bloom, 1977). Such rates of sediment accumulation can easily keep pace with rising sea levels of 3.6 and 2.2 $mm \cdot yr^{-1}$ at Eastport and Portland respectively (Hicks, 1972). When, however, the tidal amplitude is rapidly increased by major barrage construction in the Bay of Fundy, natural accretion rates of high marsh at 5 $mm \cdot yr^{-1}$ would take 20 years to reach a new MHW 15 cm higher.

If and when the proposed tidal power facility is closed and/or dismantled in some manner, the tidal regime may well revert to one which has a lower amplitude. This situation 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 high marsh, which is dominant in Maine (Nixon, 1981), 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 are also important.

III. A. 1.a. Expansion of intertidal area

Maine possesses an extensive and convoluted shoreline. It has recently been established that the length of this marine and estuarine shoreline totals approximately 6705 km (Topinka and Korjeff, 1981). The predicted increase in tidal amplitude will produce some significant changes in intertidal area. These changes, however, will not be felt uniformly among diverse Maine shore line habitats. Those shore line habitats which are characterized by steep slopes will undergo only modest absolute increases in area. Much of the Maine shoreline is characterized by rocky shoreline which is relatively steep and often has a relatively uniform slope. As a result, a 10% increase in tidal amplitude would simply extend the rocky intertidal area by 10%. In Lincoln County, whose coastline extends some 620 km, the mean slope of the rocky shore is approximately 11% (Topinka *et al.*, 1981). Assuming that a 30 cm change in tidal amplitude was to occur, this shoreline, whose rocky intertidal slope was 11%, would be extended by approximately 1.6 m. Shoreline habitats such as sand, gravel and cobble shores would similarly have their area extended by approximately 10%. Many of these areas also have often relatively steep slopes and would see only minor increases in intertidal area. Critial to this increase in area are the slopes near MHW and MLW where gentle slopes will greatly increase intertidal area on characteristically irregular shores.

Areas in which the intertidal shoreline slope is gradual will have the greatest increase in absolute area. Such regions along the coast of Maine include mudflats and salt marshes. Mudflats commonly occur as broad expanses in wave-sheltered areas. As such, a 10% increase in intertidal area will produce a relatively large absolute increases in mudflat area which will be determined by the mudflat slope.

Salt marshes will also undergo significant increases in area. In general, the 17,000 acres of salt marsh in Maine may be expected to eventually increase at least 10% to produce a gain of 1,700 acres of salt marsh 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.

III. Al.a.1) Restructuring of biological communities

A change in tidal regime will produce some significant changes in the distribution of intertidal organisms. In the intertidal, 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. 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 inhibit areas at mean water (MW) in the middle of the intertidal zone would not be moved. In the region above MW, biological zones will be displaced 10% upwards from MW. Zones of biota which are below MW will be displaced approximately 10% downward from MW. In addition to the expansion and displacement of vertical biological zones, an expanded intertidal zone will favor the development of additional vertical zones whose inhabitants have slightly different niches, e.g. requirements for immersion periods.

Major changes in zonation patterns are expected to occur along upper and lower intertidal margins. Organisms on the upper terrestrial end of the intertidal zone have very limited ability to withstand high salinity water. As high tide levels rise on the order of 15 cm., terrestrial inhabitants which are not now inundated with seawater will have their lower boundaries raised. Accompanying this will be an occupation of this upper region by marine biota which need only infrequent immersion in seawater.

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 irregularly flooded and low salt marsh areas are regularly flooded. The transition zone occurs in the vicinity of mean high water (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 but 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 borders will be extended into regions now occupied by terrestrial upper border plants.

Before new equilibrium is reached between tide level and high salt marsh regions, more higher marsh will be regularly flooded which may interfere with some shore birds. Daiber (1977) found that zones of vegetation, tide level, and salinity factors were related to bird distribution. As discussed by Nixon (1981), "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. Those shorebirds that feed on mudflat fauna could also experience some change in feeding to the extent that the abundance of food organisms was altered.

A pronounced division of biological populations also occurs near the border between the low intertidal and the subtidal. In the low intertidal it is generally considered that organisms cannot effectively penetrate into the subtidal due to their inability to withstand factors associated with constant submersion. Other factors preventing the downward penetration into the subtidal include increased competition for space and higher grazing pressure. Organisms residing in the subtidal often cannot withstand prolonged exposure to air or the accompanying stresses of dessication, variable temperature, low salinity, low light and freezing which prevents them from extending into the intertidal. The predicted 10% change in tidal amplitude will result in a lower extension of intertidal communities which will replace organisms of the upper subtidal.

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 due to massive Bay of Fundy construction will, however, not easily allow sufficient time for normal sedimentary processes to occur to produce new equilibria. 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, habitats 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.

III. A.3.b Loss of subtidal habitat

An increase in tidal amplitude will result in a decrease in subtidal habitat along the upper subtidal border. 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 be shifted downward with no real loss of subtidal habitat or associated biological populations. III. B.1.a.1)c) Surface water temperature changes

Increased tidal amplitudes will increase tidal currents in nearshore areas. In estuaries, these tidal currents will result in the greater turbulence and mixing between surface and bottom waters. In estuaries, this process should be most noticeable in summer and will be characterized by a decrease in the temperature of surface waters. The degree to which surface water temperatures will be lowered will vary between estuaries. A decrease in summer surface water temperatures in some open water regions of the Gulf of Maine may approach 1°C (Garrett. 1977). The decrease in estuarine surface water temperature in summer may be of the same magnitude. In estuaries that are already well mixed no significant change in surface water temperature would be anticipated.

A small decrease in surface water temperature would not be expected to have a profound effect on most estuarine flora or fauna. Species composition and densities would remain essentially unchanged with this temperature change. Some biota which inhabit surface waters, however, would be benefited while others may be impaired by this change. Those organisms that occurred near their limits of temperature tolerance would be affected to the greatest degree. Most organisms living in regions in which there was a temperature decrease would exhibit lowered respiratory rates and possibly lowed growth rates. Subtle changes in distribution patterns may also occur but most of those effects are expected to be slight.

III. B.1.a.1)d) Reduced retention of larvae and sexual products

Greater rates of estuarine flushing will act to disperse planktonic organisms such as invertebrate larvae of clams, mussels and commercial worms. It will also disburse other products such as sexual gametes or other planktonic juvenile forms. As a result, retention of these organisms in estuaries will decrease, lessening the likelihood that those products will 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.

III. B.1.b.1) Dispersal of subtidal shellfish beds

Greater tidally induced current velocities will increase the dispersal of subtidal invertebrate larvae including those of shellfish. Where populations of commercially valuable shellfish occur, those larval products will be transported greater distances where they may colonize new areas and recolonize areas in which shellfish stocks have been depleted. As with intertidal organisms, the planktonic products of subtidal shellfish will also be transported potentially greater distances into some regions where they would not survive.

III B.1.b.2) Development and spreading of red tide blooms

Mixing processes, particularly the formation of tidal fronts between well mixed and stratified waters, often result in accelerated growth of phytoplanton 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 massive 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 will tend to 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. Once in the water column, red tide organisms may spread over larger regions more quickly. Accompanying increased mixing of nutrients into surface waters 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 of coastal regions where the cysts may be directly consumed by organisms such as clams or mussels. Both motile cells and cysts of *Gonyaulax* may be injested 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 increased as a result of a 10% increase in tidal amplitude. It is probable, however, that red tide contamination will significantly increase in those regions where tidal currents are greatly accelerated and oceanic fronts formed. Anderson has suggested that in some estuaries, tidal current velocity may be increased by approximately 30%. Areas supporting this high level increase in velocity could witness the greatest red tide elevations.

III. B.1.c.2) Restructuring of biological communities

In sedimentary regions, bottom type and stability are determined by processes which add or remove sedimentary particles. As discussed earlier (by Anderson), an increase in tidal amplitude by 10% could influence the patterns of this sediment distribution. Many sedimentary regions, however, constitute important types of habitat which support many commercial species and many non-commercial species which are important to the function of numerous coastal processes. In the intertidal, Maine's intertidal regions and bottom areas support many diverse and productive communities of organisms. Particles from intertidal sedimentary regions range in size from clay upward to include sands of varying coarseness. Quite often these different sediments are mixed together with each other and may include varying amounts of other materials such as organic matter and stone.

In the intertidal, both wave and current action, in addition to ice scouring are important forces which influence sediment stability. The smaller, lighter sediment particles are likely to be influenced to the greatest degree. Mudflats and salt marshes having fine sediments covering large horizontal expanses and supporting important biological populations, are among the habitats most vulnerable to an increase in tidal current activity compared to those habitats having larger particles. Sand beaches will also be susceptible to increased current activity. Potentially higher rates of beach erosion could also threaten sheltered water habitats behind such beaches.

In the subtidal, sediments would also be rearranged with the greatest impacts being demonstrated in those areas exhibiting the greatest change in current activity. With both intertidal and subtidal situations, the distribution of benthic organisms is a function of habitat. Eventually, the sedimentary regime, and therefore habitats and associated benthos, 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, such a transition period could extend for many years. Once a new equilibrium is established between current regimes and habitats, biological populations would become more stable.

III. 1.3. 2. a. Increased mixing depths of surface waters

As a result of an increased tidal amplitude there will be an acceleration of tidally induced current velocities. Some of the energy from tidal currents will translate into the greater vertical mixing of the water column. Using a model developed Simpson and Hunter (1974), Garrett *et al.* (1975) examined the extent of vertical mixing that is induced by tidal action. 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 $\acute{U}^3$ is the tidal velocity-frictional parameter. This applies where heat buoyancy effects are constant. This model shows that Georges Bank and Nantucket Shoals are tidally mixed with additional mixing off the Bay of Fundy and Nova Scotia. Tidal velocities were too low water or depth was too great for other areas to be significantly mixed. 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.

In areas where tidal currents are accelerated by an increase in tidal amplitude, greater vertical mixing could occur, which in summer could bring colder water to the surface. The result would be lower surface water temperature and increased mixing depths of surface waters (destratification). Recent thought, however, has 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, personal communication). Due to the lack of knowledge concerning all of the physical mechanisms which control vertical mixing processes, it is not possible to fully quantify all vertical mixing events. It is, therefore, not possible to translate an increase in tidal amplitude into an absolute alteration of water column structure.

It is, however, possible to develop some useful perspectives on the influence of a higher tidal amplitude on the water column. Firstly, the increase in tidally induced current velocity will not be uniform in all areas of the Gulf of Maine. Other 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 deeper water a minor increase in tidal currents would not be expected to be translated into 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 must wait further investigation. It is clear, however, that increased vertical mixing of the water column will be accelerated in some areas and in these regions may lead to some small decrease in surface temperatures.

III. B.2.a.1) Reduced surface water temperature

Increased vertical mixing of the water column due to an increased tidal amplitude has been considered in the previous section. A vertical mixing process would tend to bring deeper colder waters to the surface.

The mixing of these deeper waters with water at the surface could lower surface water temperatures. This lowering of surface water temperature would 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. Where these conditions are not found, the potential lowering of surface water temperature would be less. It is clear from this and the preceding section that the significant lowering of temperature would be expected only in shallow, stratified waters, during summer and would occur on a local basis due to other physical circumstances.

The general biological effects of lower surface water temperatures in summer is given in the following section b., "Altered growth and reproduction patterns of biota."

III. B. 2.a.1)b. Altered growth and reproduction patterns of biota

Different organisms have different temperate requirements. These requirements may be expressed either as temperature tolerances near the extremes of their physiological limits or as temperature requirements needed for some specific activity such as reproduction. The effects of temperature are also pervasive and influence the physiological performances in many often subtle ways. A decrease in water temperature of 1°C may decrease respiration and many other behaviorial 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 habitats and other organisms is complex. Temperature changes on the order of 1°C will have some, probably slight, influence on many of these interactions. The total influence of a $1^{o}C$ 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 perceptable 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 $1^{o}C$ decrease in temperature may be present but not easily discernable above background variations.

III. B. 2.9.1)c. Altered fish migration patterns

Increased mixing depths could result in a decrease of summer surface water temperature on the order of $1^{o}C$ in some regions. Fish inhabiting surface waters during this time of year could be influenced. 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 inhabit surface waters in summer for significant periods would not be expected to experience attendant alteration of migration patterns.

It must be recognized that the degree to which surface water temperature would be altered by a 10% increase in tidal amplitude is uncertain. Changes in surface water temperatures will also vary greatly between different areas due to physical circumstances. Influences on fish migration patterns are accordingly uncertain.

The migratory patterns of some species of fish may also be altered by the large barrage construction in the Bay of Fundy. Dadswell and Scarratt (1982) have pointed out that fisheries of American shad, alewife, blueback herring, dogfish and formerly stripped bass could be influenced "over the entire Atlantic coast from Quebec to Florida." The extent to which these and other species could be influenced is uncertain.

III. B.2.a.1)d. Altered shipworm and fouling community activities.

In the marine environment, marine fouling organisms may attach to surfaces to 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. These fouling organisms often 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 be appreciable in sheltered water estuaries when many vessels are moored. This increase in velocity could significantly increase the level 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. These factors would tend to increase the numbers of fouling organisms. 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 these temperature influences would be small compared to the direct influences of current velocity.

III. B.2.a.2 Vertical transport of water borne substances

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 functional resistance while flowing over the bottom. Diffusion refers to the process of one substance mixing with another by the movement or penetration of that substance between another substance 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 an increased tidal regime would be to increase current velocities where these currents encounter resistance of boundaries near the surface or at the bottom. This turbulence and the turbulent mixing it produces will be the most important advective force which accelerates 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.

The extent of vertical transport in the water column is subject to many of the same factors and uncertainties discussed in the section on "decreased mixing depths of surface waters." If waters are already well mixed, transport is being facilitated and may not be significantly accelerated by greater mixing. However, where barriers exist to transport, as stratification of surface waters in summer, increased vertical mixing could increase vertical transport. Unfortunately, the absolute magnitude of transport changes remain complex and uncertain. In general, areas in which higher tidally induced current velocity, shallow waters, and greater stratification occur would be expected to experience the most significant increase in the vertical transport of water borne substances. Other physical circumstances, locality, and substance density and substance type will also be important in vertical transport.

III. B.2.a.2)a. Increased nutrient supply to surface waters

Increased tidal currents resulting from higher tidal amplitude 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. Higher tidally induced current velocities would be expected to bring additional nitrogenous nutrients from sediments and deep waters into surface waters to increase phytoplankton growth. In a similar manner, the availability of other dissolved nutrient substances to phytoplankton would also be increased. III. B.2.a.2.b. Transport of pollutants to bottom sediments

In regions which are not vertically mixed, 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 has to do with the fact that pollutants are now spread more quickly to reach a greater area and a larger number of potentially vulnerable organisms. 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.

Higher current velocities near the bottom will increase bottom turbulence which will tend to maintain the 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 well drilling. Higher bottom turbulence, however, could also act to move and mix bottom sediments at faster rates. This would mean that denser particulate substances which do settle to the bottom could be mixed into bottom sediments more rapidly.

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 weather and mix with water column substances and sink to the bottom at faster rates. There it would mix with bottom sediments. Under anoxic conditions many oil components could persist for many years.

III. B.2.a.3 Transport of other products to the euphotic zone

The upward vertical transport of dissolved, neutrally buoyant or positively buoyant substances would be facilitated by greater vertical mixing. This could be important for any substance which is produced or released at greater depths and whose vertical concentration gradients is not uniform throughout the water column.

Of particular interest here is the affect of increased vertical mixing on red tide development. The red tide organism *Gonyaulax* is transformed into a resting cyst stage when growth conditions are poor. These cysts settle to the bottom and commonly reside on or near the sediment surface. Increased tidal velocities will tend to put more of these cysts into suspension. Increased turbulence and vertical mixing could transport more cysts into the euphotic zone where they may find more favorable conditions under which to excyst and grow. The result could be greater numbers of red tide cysts in the water column and the greater likelihood of red tide bloom formation.

III. B.2.a.4.b. Changes in scattering layers

Some scattering layers occur as the result of the vertical distribution of organisms with the water column. These organisms often occur at high densities and are arranged as definite layers. Fish having air bladders filled with air are often responsible for major scattering layers. High resolution sonar may also register other organisms such as zooplankton. A change in the vertical mixing process, as it influences the biological and behavioral patterns of scattering layer organisms, may alter the the depths of some scattering layers. For reasons discussed in the section "Increased mixing depths of surface waters," the influence of vertical mixing on the position of scattering layers would not be significant in many regions for most of the year.

Moreover, deep scattering layers would not occur in shallow regions most susceptable to changes in the vertical mixing process.

IV. A.4.b. Shell-fishing

The impact of a 10% increase in tidal amplitude on intertidal mussels and clams is discussed in Section IV, A.5. Shrimp, lobster, crab and scallop industries may also be influenced by a change in tidal regime. The acceleration of tidally induced current velocities is likely to increase vertical mixing processes of the surface and/or bottom waters. This increase in vertical mixing could stimulate primary productivity of phytoplankton. Primary production of food by salt marsh plants and seaweeds would also be expected to occur. 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. Higher current velocities could also increase distribution of plankton, juvenile and adult stages. Additional suspension of organic matter in the water column and higher current velocity could supply more food to filter feeding organisms like shrimp and oysters, thereby stimulating growth.

IV. A.4.C. Anadromous fishing

Anadromous fish swim up estuaries for spawning purposes. As such 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 should 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 and also result in anadromous fish having to swim additional distances. 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."

IV. A.5. 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. A direct increase of 10% in the standing stock of these organisms is therefore 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 these organisms. Higher current activity would also be expected to bring more 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 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 gain of at least 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.

IV. A. 6. Seaweed collection

A 10% increase in tidal amplitude should increase the area over which rocky intertidal seaweeds grow. This alone should increase the intertidal seaweed biomass by 10%. Included, would be an increase in standing stock of Irish moss (*Chondrus 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. 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 organism. 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.

IV. A. 7. Aquaculture

The major aquaculture industries in Maine are those involving mussels and oysters. A 10% increase in tidal amplitude would be expected to increase growth rates of these organisms. 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 increase of growth. A potential decrease in icing conditions would also be of some benefit to these industries. Red tide problems, however, might be increased as previously discussed. Mussels and oysters would be subjected to potentially greater blooms of red tide and would be exposed to greater numbers of red tide cysts. Injestion of either motile, growing organisms, or cysts could increase shellfish toxicity (Lewis *et al.*, 1979).

Research Needs

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. While it is possible to make general statements concerning the types and gross magnitudes of potential effects, no quantitatively rigorous treatment of many areas of concern is often scientifically advisable. 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 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.

With this in mind, the following presents a list of scientific and economic issues that must be resolved. Included are specific research needs and the economic concerns which must ultimately be addressed.

1. Increases in intertidal will occur as the result of higher tidal amplitude. It is necessary to know how much of the various intertidal regions will be increased in terms of area. Also, how much area will be lost to subtidal and terrestrial borders?
2. As a result of aerial changes in intertidal habitats, biological populations will be altered. What will be the precise nature of these biological alterations?
3. Increased tidal flushing of estuaries will take place, which will disperse pollutants faster and may increase primary productivity of organic food matter. To what degree will flushing be changed in various estuaries and how its pollution dispersion and primary productivity be altered?
4. Using the Greenberg model, an attempt should be made to assess tidal current velocities and their attendant influences on vertical mixing process in the Gulf of Maine. What changes in surface and bottom mixing will take place?

5. As a result of accelerated vertical mixing, surface water temperatures may be decreased in summer. How much will they be decreased, over what aeral extent and over what period?
6. Much of the summer phytoplankton production in the Gulf of Maine occurs along oceanic frontal regions and in regions which are vertically well mixed. What magnitude of primary production increases are likely to occur as the result of increased tidally-induced vertical mixing?
7. Increased tidal amplitude could result in new distributions and growth rates for intertidal and subtidal flora and fauna. To what extent will major benthic components be changed?

Environmental Planning and Public Education Needs

It is the function of the scientific community to provide data and insight on environmental issues in an objective, unbiased way. With information provided by the scientific community, it is the responsibility of the people and their government agencies to weigh the importance of issues and make needed value judgements. With this in mind, it is necessary that public awareness of important issues, such as tidal power, be increased. In the past, the news media have taken this role, but have many times misunderstood and inadvertently distorted the issues involved. In the future, it may be advisable to release prepared statements or articles which most accurately reflect the concerns of the scientific community and government. Literature, comprehensible to the layman, should also be made available. This will serve the best interests of the public.

With the input of concerned citizens and groups, state agencies such as the State Planning Office should assume lead roles in forming policy decisions. This is necessary due to the complexity of tidal power issues. Many technical factors of a complex problem must be assimilated. The expenditure of time and effort required for this assimilation may well prevent most citizens from developing a comprehensive perspective on tidal power issues. It must also be the responsibility of government agencies to see to it that the more dramatic, but perhaps less important issues not be allowed to dominate decision making progress.

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