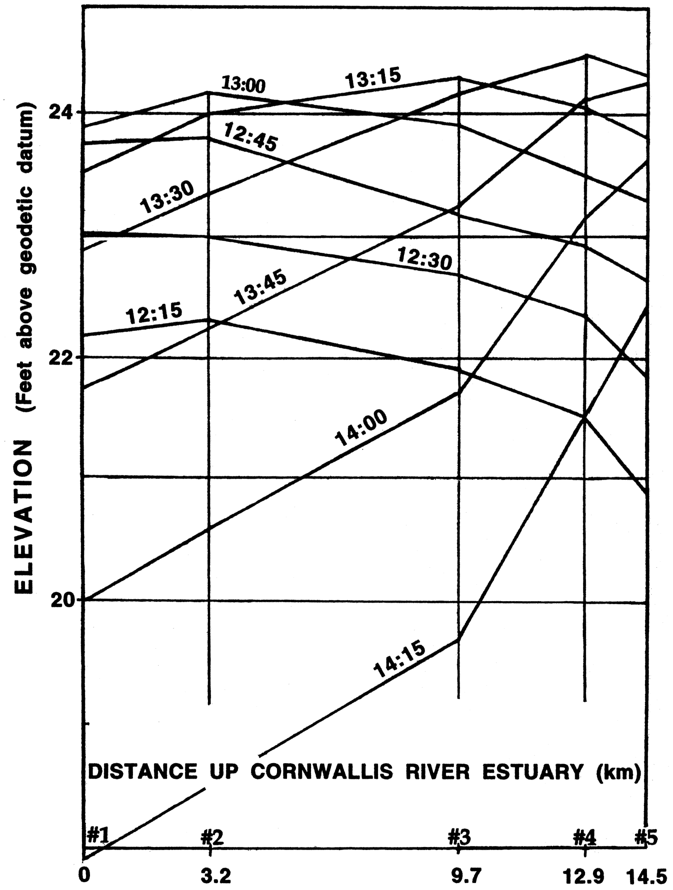


Fig. 38 Observed water surface gradients at different stages on the Cornwallis River, Nova Scotia, using measurements taken only near the peak of the tide, on 5 September, 1956. (Times tie in with those shown in Fig. 36). Note the relatively uniform gradient of the water surface of the rising water (time 12:15 to 13:15) compared with the progressively steeper gradient during reversed flow in the channel. Locations: #1, 0 mi (0 km) mouth of the Cornwallis River; #2, 2 mi (3.22 km) upstream; #3, 6 mi (9.65 km) upstream; #4, 8 mi (12.87 km) upstream; #5, 9 mi (14.48 km) upstream. High water on the Saint John River was 27.4 ft + CD at 11.43 AST.

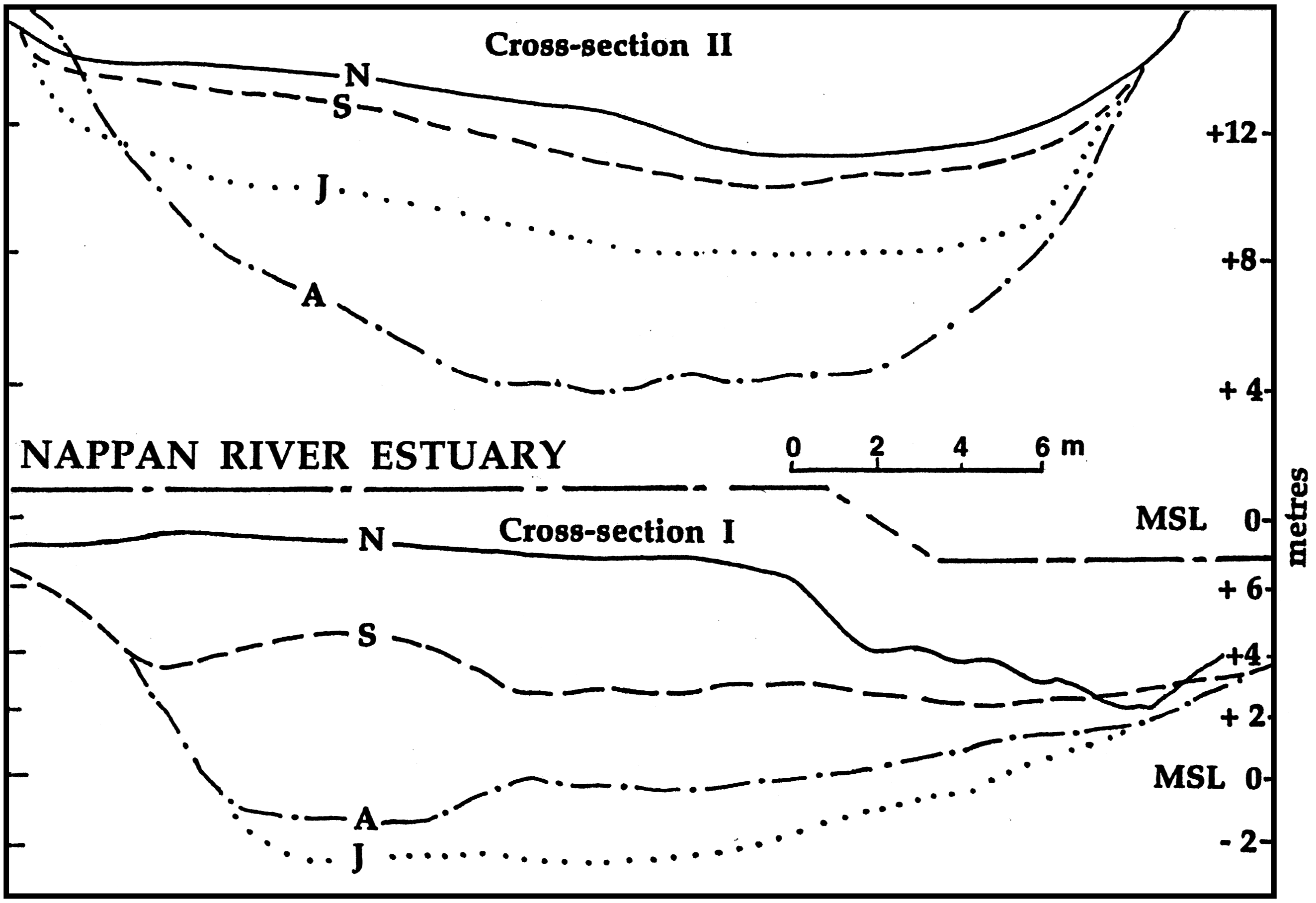
ing a natural levee. Thus a pond is formed between the tidal estuary and uplands. With submergence of the landmass, the levee becomes higher, and the pond, which receives thinner layers of fine-grained material, becomes deeper and extended horizontally. At a late stage of development the far reaches of these ponds receive hardly any salt water, thus allowing freshwater vegetation a chance to develop.

7.3. THE REVERSING FALLS – A UNIQUE ESTUARINE FEATURE

The Reversing Falls at the mouth of the Saint John River, N.B. is a perfect example of what happens when an estuary of limited cross-sectional area must serve a tidal prism with a large surface area. It was on Jean Baptiste day, 24 June, 1604, that the first Europeans in the region, Pierre de Gua, the Sieur de Monts, a Huguenot merchant, and Samuel de Champlain, Royal Geographer, discovered the mouth of one of the largest rivers on the eastern seaboard of North America. These pioneers and others who came later described its mouth in their logbooks and reports. According to the Jesuit missionary Pierre Baird (1611), "The entrance to this river is very narrow and dangerous, for a ship has to pass between two rocks, where the current is tossed from one side to the other, flashing between them as an arrow. Upstream from the rocks is a frightful and horrible precipice, and if you do not pass it at the proper moment, and when the water is smoothly heaped up, of a hundred thousand barques not an atom would escape, but men and goods would all be lost." (Raymond 1910). Doubtless Baird was well aware of the Indian legend concerning the hazardous entrance to Saint John Harbour. Here the Indian cultural hero Glooscap is said to have created the Reversing Falls when he destroyed a large beaver dam built across the river's mouth. (The remains of Glooscap's beaver dam support a popular restaurant!) The natural feature responsible for the legend lies at the downstream end of a 4 km long, tortuous river section. At Indiantown, water surface levels can vary between 0.3 m above Geodetic Survey of Canada Datum (GD) during periods of small river discharges, to 5.2 m above GD during extremely large runoffs. Two kilometres downstream of Indiantown the river suddenly narrows to 215 m, and a sill occurs about 4.5 m below GD (see Fig. 40). Downstream of this sill the channel deepens to 45 m below GD and steep rocks conspire to form a gorge 106 m wide, with the bottom 40 m below High Tide level and a cross-sectional area of 2125 m^2. During Low Tide the river at the reversing Falls is only 78 m wide and the cross-sectional area reduced to a mere 1400 m^2 (Fig. 41).

The average freshwater discharge of the Saint John River is approximately 1100 ms^{-1}. In spring, the melting snowpack in the watershed, combined with precipitation, can generate freshets of more than 10 000 m^3/s. The cross-sections over the sill and in the gorge are far too small to allow these storm discharges to pass at normal levels, which are little above MSL. Therefore at times the water has to rise over 5 m, even during low water, before such freshets can fully discharge into the sea. Even then, tides restrict the outflow twice a day during High Water. The average range of tide in Saint John Harbour is 6.7 m, reaching an elevation of 3.4 m + (above) GD. Large tides have a range of 9.1 m and reach 5 m + GD.

Upstream of the falls a system of drowned valleys (Grand Bay, Kennebecasis Bay, Long Reach and Belleisle Bay) provides drainage channels for the river and some of its tributaries. They have a combined surface area of 200 km^2 at the present sea level, and 250 km^2 at flood levels about 5 m above GD. Due to sea-level rise this system has gradually been filling over the past several thousand years. The tide has a range of about 0.5 m, but in the section of river upstream from Evansdale it is reduced to 0.3 m, and half that again 10 km further upstream. Upstream of the Falls the tidal prism is approximately 0.09 km^3, and can be filled within 6.2 hours by an average flow of



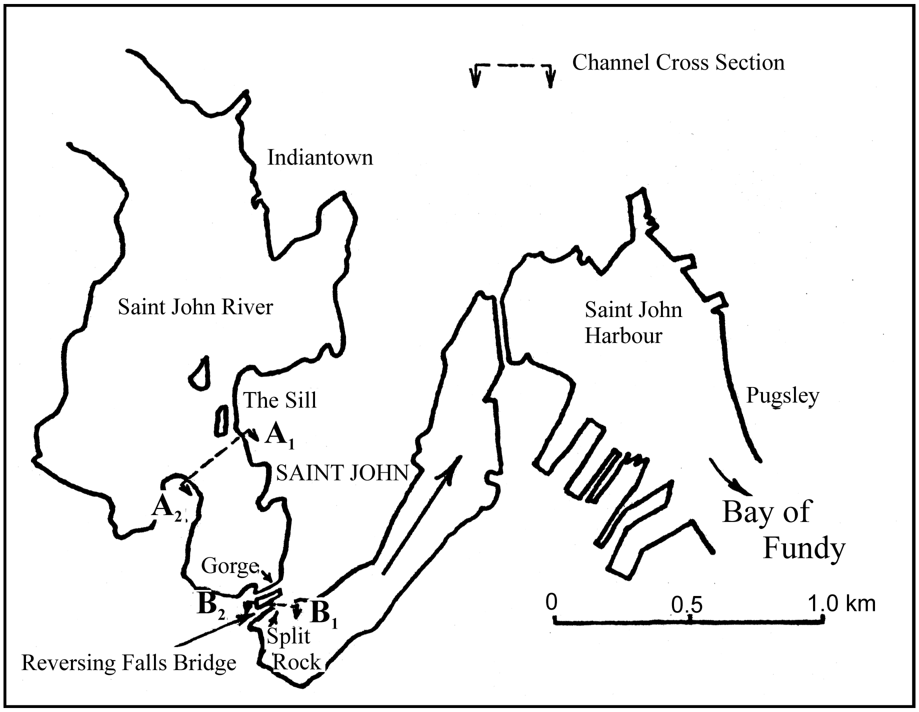


Fig. 39 (Above) Two cross-sections of the Nappan River estuary, N.S., measured before construction of the aboiteau in the Nappan River near the highway Amherst West-Amherst Point-Nappan. The measurements, taken at four different times (A=April, J=June, S=September, N=November) in 1956, reflect the varying amount of sediment build-up versus erosion. I) One mile (1.61 km) from the river mouth, II) Four miles (6.44 km) from the river mouth. Measurements refer to MSL and were taken from bridges. Data from MMRA archives. Horizontal scale = 2 x vertical.

Fig. 40 (Left) Index map to the Reversing Falls on the Saint John River, N.B. See Fig. 41 for view of cross-sections A_1–A_2, and B_1–B_2.

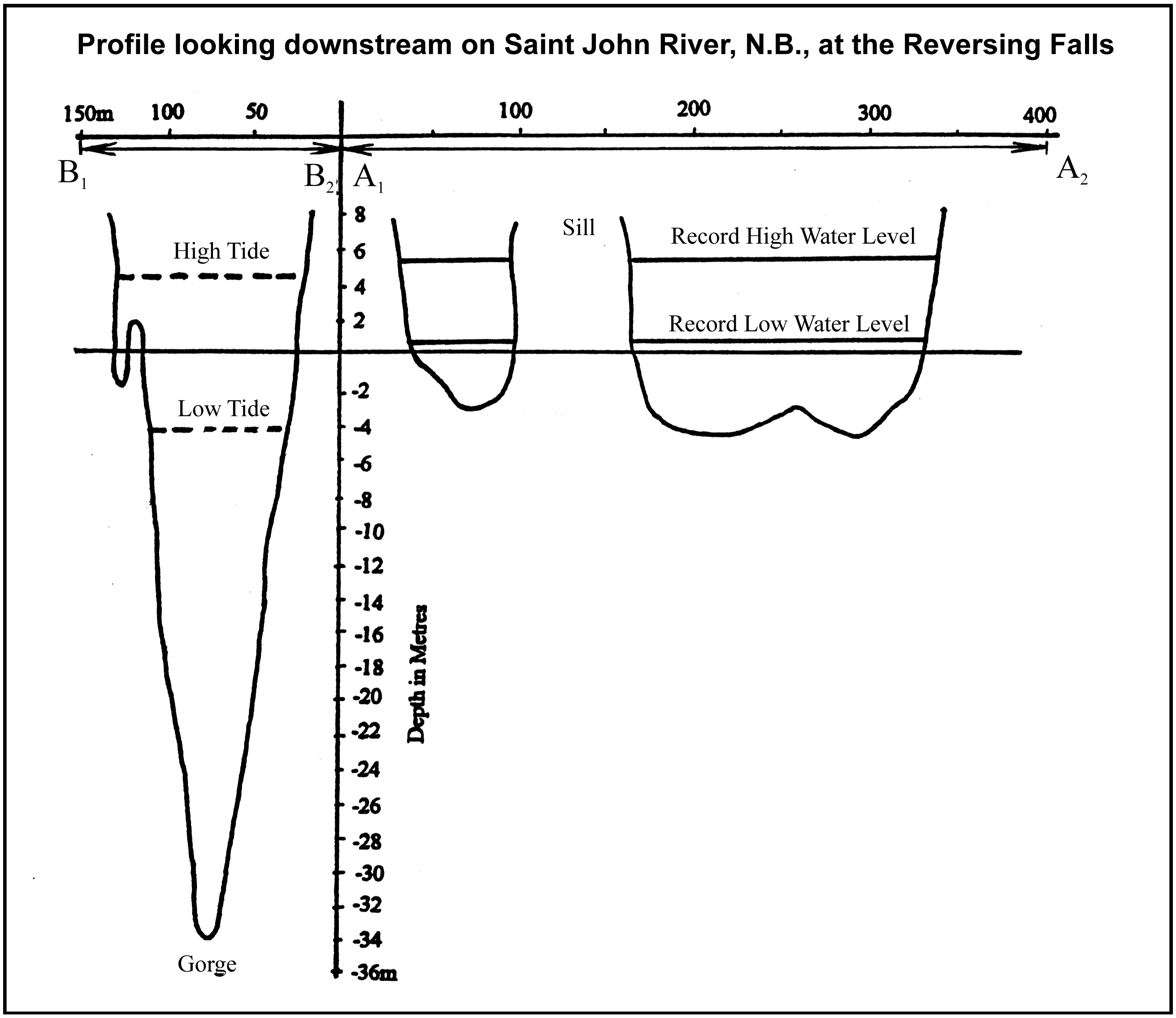


Fig. 41 Cross-sections showing the sill (A$_1$–A$_2$, Fig. 40) and the gorge (B$_1$–B$_2$, Fig. 40) at the Reversing Falls, Saint John, New Brunswick. Vertical exaggeration is 10 x.

4000 m^{3}s^{-1} with an average velocity of 5.5 ms^{-1} through the area of 730 km^2 over the sill, requiring a drop of 1.5 m (Hansen 1970). When the river is low and with only a small gradient in the water surface, backwater effects due to the tides are observed near Fredericton, New Brunswick's capital, 125 km upstream of the falls.

In Saint John Harbour the tide ranges from −2.0 m to +2.0 m with respect to MSL during small tides and from −4.5 m to +4.5 m during large tides. Upstream of the falls the range is at most between 0.0 m and 0.6 m above MSL. This means that at High Water in the Harbour, the water will flow through the gorge and over the sill in a landward direction, dropping 1.75 m to 4.2 m depending on the strength of the tide. But at Low Water in the Harbour, the water will flow seaward dropping over a short distance 2.3 m to 4.8 m. Tidal water, augmented by the river discharge, gains a considerable velocity when moving over the sill where the available wet cross-sectional area is smallest. Rapids result in this section as the water moves turbulently through the gorge into the Harbour.

Navigation under these conditions clearly poses problems. Since tidal current and river flow are always present, there is no appreciable slack water in the Reversing Falls section. The ideal time to navigate the section is as close as possible to the time of slack water as indicated in the tide tables. Slack water at the end of the inward current is 2.4 hours after the time of High Water predicted for Saint John. The tide has then dropped sufficiently to be close to the same level as it is in the river upstream of the falls. Another slack time occurs 3.8 hours after Low Water, when the tide has reached the river level. Although slack water lasts less than 10 minutes, the section can be navigated for half an hour before and after this slack. Variations in meteorological conditions can alter the time of slack water by up to about an hour. At times it is impossible for ships to move upstream. An example is during spring runoff when river levels upstream of the falls are so high that they are not even reached at High Water levels of the tide. Under these conditions a steady seaward current will persist throughout the whole tidal cycle.

Flooding of the several lakes upstream on the Saint John River has troubled settlers on the fertile freshwater delta since 1694. In April 1987 heavy flooding associated with an ice jam caused water levels to rise over 5 m. The basic problem was recognized as early as 1693 by Lamothe Cadillac who, while conceding that the Saint John is the most beautiful, most navigable, and the most favoured river of Acadia, was all for blowing up the rock on which the Reversing Falls restaurant is situated. Indeed, the idea has been revived on more than one occasion since. Fortunately there has been strong opposition. People perceive that such a project would change the Saint John River into a tidal river with unsightly mud flats and alternating currents of turbid water. The remedy for protecting the low-lying lands would be worse than the problem because the annual inundation with fresh water would be replaced with inundations of salt or brackish water at every set of high tides. Moreover the Harbour would be ruined because tidal currents would become much stronger than they are at present, increasing the navigational hazards. For these good reasons the Falls remain a unique estuarine feature of the Fundy landscape.

7.4. TIDAL POWER

Tidal energy, exploited in Europe over 900 years ago, is highly predictable and is harnessed in much the same way as hydropower; all that is needed is a barrage across a suitable estuary that allows the bay behind it to alternately empty and fill with the tides. The greatest amount of energy available from falling water, at least in theory, is obtained by dropping the largest amount possible over the greatest vertical distance (Daborn 1977).

The construction and operation of a tidal power plant is however much more complex than a hydro plant on a river. At a given site, the amount of energy available depends on the range of the tides and the area of the enclosed bay. Since the head can never exceed the tidal range, unless water is pumped from the sea into the reservoir using energy generated elsewhere, the capacity of the plant can only be increased by moving more water through the turbines. This water must move by tidal action, within the period of 6 hours or less, from the sea into a reservoir when the sea levels exceed the reservoir levels. This water must then be temporarily stored in the reservoir until the tide drops enough to create a head that will drive the turbines. The larger the reservoir, the more power the plant can extract from the water. In principle it would be best to build the barrage at a point in the estuary close to the sea. Most estuaries flare and deepen toward to sea, requiring the barrage to be more voluminous and therefore more expensive and challenging to build. No matter what the location the control of tidal waters through the channel, particularly during the late stages of construction of the barrage, is extremely difficult. High tides during this construction period force large amounts of water through the closure gap. Nevertheless, in order to make a tidal power plant energy effective, an estuary is needed where large tides prevail. To illustrate (Bray *et al.* 1982; Gordon 1984; Gordon and Dadswell 1984), large sections of estuaries in the Bay of Fundy fall dry at Low Water. When the tide rises, the surface area of the water gradually increases. In most cases the water surface area for a trapezoid is approximated as follows:

$$Sy = (M + N \cdot y) \cdot 10^6 \text{ m}^2 \tag{40}$$

where M = surface area in km², at MWL, N = increase in surface area in km²/m, y = the height above MWL in metres. The volume R of a tidal section between levels a and b (see Fig. 42) is approximately:

$$R = [M + N(a + b)/2] \cdot (a - b),$$

whence

$$R = [M \cdot (a - b) + N \cdot (a^2 - b^2) / 2\,] \cdot 10^6 \text{ m}^3 \tag{41}$$

or where b is negative,

$$R = M\,(a + b) + N\,(a^2 - b^2)\,/2 \cdot 10^6 \text{ m}^3$$

The tidal prism P, with a total amplitude of A metres then becomes:

$$P = 2A \cdot M \cdot 10^6 \text{ m}^3 \tag{42}$$

In the upper reaches of the Bay, the volumes of R and P can be large. Examples are given in Table 16 together with the values of potential energy Ep, during MHW.

The energy in a body of tidal water can be compared to the energy in the pendulum of a grandfather clock. The weight, or bob of this instrument, with mass m, is suspended a distance L from a rigid support. If the system is at rest, the force of gravitation will keep the bob at its lowest position, exactly vertical, below the support. However when the bob is drawn aside a distance x, it has to be lifted the vertical distance y. The relationship between y, x, and L can be expressed as:

$$y = L[1 - (1 - (x/L)^2\,)^{0.5}] = L\,(0.5\,(x/L)^2) \\ + \text{much smaller terms.} \tag{43}$$

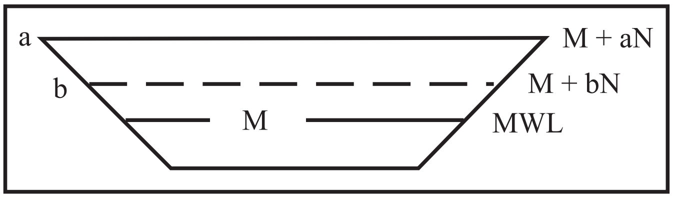


Fig. 42 Cross-section of trapezoid shows: surface area M, at MWL, and at two higher levels a, and b; N represents the increase in surface area.

Table 16. Characteristic water surfaces, tidal prisms, potential energy, etc., of various sections of the Bay of Fundy

	M km^2	N km^2/m	Mean A m	P km^3	R+MSL km^3	R-MSL km^3	Ep 1014 J
Cobequid Bay	210.6	14.6	6	2.53	1.53	1	0.487
Southern Bight	157.3	9.4	6	1.89	1.11	0.77	0.353
Minas Basin	608	8.8	5.5	6.69	3.48	3.21	0.973
Total Minas Basin	975.9	32.8	5.8	11.11	6.12	4.98	1.813
Cumberland Basin	78.3	8.0	5	0.78	0.49	0.29	0.132
Shepody Bay	115.2	8.4	5	1.15	0.68	0.47	0.18
Chignecto Bay	280.5	2.2	4.5	2.52	1.28	1.24	0.292
Total Chignecto	474.0	18.6	4.8	4.45	2.45	2	0.604
Inner Bay	4653.8	6.4	4	37.23	18.67	18.56	3.755
Subtotal	6103.7	57.8	4.4	52.79	27.24	25.54	6.172
Outer Bay	6976.1	10.3	2.5	34.88	17.47	17.4	2.196
Total Bay	13079.8	68.1	2.9	87.67	44.71	42.94	8.368

Notes. M = surface area in km^2 at MSL; N = increase in surface area in km^2; A = amplitude of the tidal prism; R = volume of a tidal section between levels a and b; MSL = mean sea level; R + MSL is the volume between MSL and tide level + A; R - MSL is the volume between MSL and tide level - A. (R + MSL) + (R - MSL) = P. E_p = potential energy

The potential energy E_p is equal to 0.5 m · g · x²/L, and the kinetic energy E_k can be given as 0.5 m (dx/dt)², when x is small compared with L. The total energy is then the sum of E_p and E_k, and can be expressed as:

$$E_t = 0.5\ m\,(g \cdot x^2/L + (dx/dt)^2) \qquad \textbf{(44)}$$

indicating a simple harmonic motion. When the bob, with a mass of 1 kg, and suspended 1 m below its support, is moved aside horizontally 0.44 m from its equilibrium position, it must be lifted 0.1 m, thus being supplied with an energy of 0.1 · g Joules. When released it will be accelerated, reaching its maximum velocity of 1.4 ms^{-1} when passing its equilibrium position. This velocity enables the bob to be lifted 0.1 m at the other side of the equilibrium position. In the clock, the energy lost due to friction with the support and the surrounding air, is replenished by a dropping weight via the escapement mechanism. When the motion of the bob is interrupted at the equilibrium point, the system is released of its total energy. In order to start the bob moving again, the same energy must be resupplied.

A body of tidal water can be likened to a pendulum lying on its side. At Mean Sea Level, its equilibrium position, the strongest currents occur and thus the maximum amount of kinetic energy (Godin 1990). The highest potential energy occurs when the surface is close to its High Water or Low Water positions. In order to reach its Low Water position, the water must be evacuated toward the sea by means of its current velocity. The water then has to move uphill, decelerate, and eventually come to a halt, thus limiting the volume that can be evacuated near the head of the estuary. Because this movement causes eddies and friction, the oscillating tidal movement can only be maintained when fresh supplies of energy are introduced into the system by the oceanic tides. Nor is all of the energy dissipated during each tide, otherwise the outgoing water would not have the energy to move uphill during the latter half of the ebb cycle and a noticeable imbalance between the High Water and Low Water amplitudes would result. There should also be a relatively large dissipation of energy otherwise the tide would not respond as fast as it does to the changing gravitational influences of the Moon and Sun.

The energy E_1, of a layer of water with velocity v, density D, a surface area S_y km², d_y metres thick, at elevation y, with the capacity of dropping a vertical distance h, and subjected to an atmospheric pressure p kPa, can be described as:

$$E_1 = (D \cdot g \cdot h + p_1 + 0.5\ D \cdot v_1^2) \cdot S_y \cdot d_y \cdot 10^9 \text{ Joules} \qquad \textbf{(45)}$$

When the water is moving from a deep reservoir through the turbines, the original velocity v_1, of the water in the reservoir, is negligible in relation to the current velocity v_2 that it has when leaving the turbines after the h metre drop. The atmospheric pressure p_1, affecting the water in the reservoir, will be on average around 101 kPa, with possible deviations of 4 kPa. However the pressure p_2, in the turbines can be much lower because of the Venturi-shaped passage. The drop in pressure can account for the measured discharge coefficients of such orifices, which can considerably exceed unity. Generally velocities in such passages can not be higher than $(2g \cdot h)^{0.5}$, but certain shapes allow underpressures and higher velocities.

After the water has dropped the distance h, the energy changes in character. The potential energy Ep, represented by the factor $D \cdot g \cdot h$, is transformed into other energy forms, such as kinetic energy E_k, or heat energy E_h; it can also be extracted as electric energy E_e. Consequently the energy distribution E_2 after the drop h, becomes:

$$E_2 = E_1 = (p_2 + 0.5\ D \cdot v_2^2) \cdot S_y \cdot d_y \cdot 10^9 \text{ Joules} \qquad \textbf{(46)}$$

Thus, the potential for electrical extraction will be:

$$E_e = (D \cdot g \cdot h + p_1 - p_2 - D \cdot (v_2^2 - v_1^2)/2) \cdot S_y \cdot d_y \cdot 10^9 \text{ Joules} \qquad \textbf{(47)}$$

Neglecting energy gain due to pressure differences, and assuming negligible initial velocity v_1, the energy that can be extracted annually (706 tides) with a single-effect operation can be set at:

$$E_e = 1971.3\ (h - v_2^2/(2g)) \cdot S_y \cdot d_y \text{ MWh / year} \qquad \textbf{(48)}$$

Note that no energy extraction is possible when $v_2 = (2g \cdot h)^{0.5}$. To extract the largest amount of electric power, the value of v_2 must be kept as small as possible. If the combined working cross-sectional area of all turbines is X m², and extraction occurs during t seconds, the velocity , v_2 will be:

$$v_2 = S_y \cdot d_y \cdot 10^6 / (X \cdot t) \text{ m/sec} \qquad \textbf{(49)}$$

The velocity will decrease as the values of X and t increase. Because it is not possible to extract all of the energy during the relatively short interval of slack Low Water, sufficiently large discharge channels must be available. Obviously, it is not practicable to employ the total tidal range as an energy head.

Another interesting and important consideration concerns the value of $N \cdot y$ in **(41)** for S_y. When $N \cdot y$ is large relative to M, the potential for extraction of energy on the ebb flow becomes much more attractive than during the incoming flood flow because of the larger surface areas at higher levels of the reservoir. Double-effect extraction is less attractive (Larsen and Topinka 1984; Charlier 1982) because, although more time is available for extraction, the available head will be smaller, and very large sluiceways are needed in order to fill and void the reservoir of large volumes of water during shorter intervals.

Promoters of tidal power usually use the following simplified equations for calculating the potential energy extraction. Here it is assumed that the base level to which the water in a reservoir can fall is at elevation z, and that the total energy E_e can be derived by the integration of the following equation:

$$dE_e = K \cdot (M + N \cdot y) \cdot (y - z) \cdot d_y \text{ Joules} \qquad \textbf{(50)}$$

where $K = D \cdot g \cdot 10^9 = 10.05 \cdot 10^9$. When y drops from level a to level b, the value of E_e becomes:

$$E_e = K \cdot (M - N \cdot z)(a^2 - b^2)/2 - M \cdot z \cdot (a - b) + N \cdot (a^3 - b^3)/3 \text{ Joules} \qquad \textbf{(51)}$$

If the range of the reservoir is Y and a = Y/2, and b = z =– Y/2, then **(51)** becomes:

$$E_e = K \cdot (M \cdot Y^2/2 + N \cdot Y^3/12) \text{ Joules} \qquad \textbf{(52)}$$

For a single-effect operation during 706 tides, the annual output can be estimated at:

$$E_e = 3.548 \cdot 10^{12}\ (M \cdot Y^2 + N \cdot Y^3/6) \text{ Joules /year} = 0.9856 \cdot 10^6\ (M \cdot Y^2 + N \cdot Y^3/6) \text{ kWh/year} \qquad \textbf{(53)}$$

Promoters may replace Y by the tidal range, and use twice the value, indicating a double-effect operation in which the reservoir is emptied simultaneously at Low Water, and filled again instantaneously at High Water. This yields a highly inflated value of the potential power extraction.

7.5. PROSPECTS FOR FUNDY TIDAL POWER

Greenberg (1987) has calculated the mean potential energy of the Minas Basin at $1.15 \cdot 10^{14}$ J per tide. For a smaller area (850 km², east of Cape Split), Godin (1990) estimated energy output at $2.657 \cdot 10^{14}$ J. The theoretical potential energy for this area, calculated using (52), and Y as the local amplitude of the mean tide, is $1.8 \cdot 10^{14}$ J per tide. However, Charlier (1982) claims that a total annual energy of 169.5 billion kWh can be generated (this is equivalent to about $8.65 \cdot 10^{14}$ J per tide) with a double-effect unit.

A single-effect power station lets the water flow through the turbines in one direction only, generally from the basin into the sea, thus utilizing the greater basin storage at the higher levels. Since the amplitude of the tide can vary between 60 and 140%, its mean potential value can be even higher. As the output is proportional to the square of the amplitude, the importance of a large tidal range becomes obvious (see Table 16). Tidal range is even more crucial in areas where the water surface area increases significantly. In practice of course all this energy cannot be tapped. This would require the reservoir to be filled to high tide level, and then almost instantaneously released when the tide is out.

Experts on tidal power development estimate that only about 25 to 30% of theoretical capacity can be realized. For example, the French tidal power station on the Rance River has a basin with a surface area of 22 km² and a mean tidal amplitude of 4.25 m. The theoretical annual energy output should thus be 1567 GWh. However with an annual output of 544 GWh, the efficiency is close to 35% thanks to refined computer software, which optimizes plant operation, including pumping and double-effect power generation. A similar system is operated by the Russians in Kislaya Bay, near Murmansk. It has a 1.1 km^2 basin and a theoretical annual output of 6775 MWh of which only 2300 MWh is realized. The Russian and French tidal power stations operate with reservoirs used as holding ponds to create large heads, and turbines to extract the energy.

Alternate Fundy tidal power proposals call for placing paddle wheels or egg-beater-type propellers in the flowing water, without confining the water to either reservoir or restricted channel. One possible location is the Minas Channel, where current speeds can reach 7 to 8 knots. A current speed of 8 knots can be generated by a head of 0.86 m. Theoretically, by building a dam in the Minas Channel, a head of 10 m can be created. This is 11.5 times the head that the paddle wheel can be subjected to under the fastest currents. Nevertheless, in 1916 the president of Acadia University, together with two members of its engineering department and the head of its business academy, formed the Cape Split Development Company. During summer, a survey was made of the topographical and hydrographical conditions between Cape Split and Squaw Cap Rock (just offshore from the Cape). The maximum tidal current was clocked at 11 mph (4.92–5.66 m/sec). A model was constructed of a tidal power contraption consisting of pairs of endless chains linked to concave vanes and led over sprocket wheels that would drive pumps. The idea was that the pumps would continually top up two 250 000 m^3 storage tanks erected on the 100 m high Cape Split. Water would generate electric power utilizing machinery built in four open sluices and housed in the 120 m-wide gap between Cape Split and Squaw Cap Rock. Although shares were quickly issued, the company dissolved in 1929.

There were a few early success stories relating to tidal power worldwide. Records show that tide mills existed on both sides of the English Channel as far back as the 12th Century. Similar mills were also in operation along the coastline of eastern North America shortly after the first settlers arrived. Some of the mills served several purposes. In 1634, a cove and marshland north of Boston were dyked off. A three metre-wide sluice admitted tide water, which eventually powered two grist mills, a saw mill, and a chocolate mill. Most of these plants were abandoned when more convenient sources of energy became available.

A modest proposal for Fundy tidal power was advanced by K.E. Whitman in 1944 for a double-basin scheme using the Maccan River estuary as a head-water pond and the Hebert River estuary as the tail-water basin. Hicks (1965) identified seven possible sites between Cape Split and the mouth of the Bay of Fundy, and between Long Island, N.S., and Cutler, Maine. That same year it was seriously proposed to build a barrage through the 5 km-wide Minas Channel. The channel is 100 m deep at low water, and a suggested dam at this site would have a volume of over 75 million cubic metres! At that date, only the Fort Peck dam in the U.S.A. was more voluminous. To handle the volume of material needed in construction would require exclusive use for two years of loading facilities equivalent to all those available at the world's largest shipping centre, Rotterdam.

There have also been proposals based on the difference in tidal range on opposite sides of the Chignecto Isthmus. Tides in Cumberland Basin have an average range of 10 m, while 23 km away, in the Northumberland Strait near Baie Verte the average range is less than 5 m. Many people have had the mistaken idea that the Low Waters of these tides are at the same level as the Fundy tides, tides on both sides of the isthmus being measured from Chart Datum. The fact is that each tidal station has its own Chart Datum set at some particular elevation below Mean Sea Level. (Chart Datums are set at elevations so low that the tide at any given location will seldom if ever fall below it). Thus, and contrary to some proposals that have actually been advanced (see for example, Pogany 1958), the perennial economic problems of the Maritime Provinces can not be solved by simply digging a canal through the isthmus and installing a tidal power plant on it.

A more thoroughly researched report was prepared in 1945 for the Government of Canada (H.G. Acres and Co. 1946) concerning tidal power development in the Petitcodiac and Memramcook River estuaries. However this report, like that prepared by the Atlantic Tidal Power Programming Board (1969) for the Federal and Provincial governments, concluded that development could not be justified under the prevailing economic circumstances. A different conclusion was reached in the Bay of Fundy Tidal Power Review Board (1977). Out of 37 possible sites, the three most promising were in the Minas Basin, Cumberland Basin, and Shepody Bay. According to the report (which really focused on the results of market research), the largest, in the Minas Basin, would be capable of generating about 5000 MW; it was given preference over runner-up Cumberland Basin.

Many proposals have been advanced to try and tap the power of the Fundy tides (for details see Desplanque and Mossman 1998a). To date, however, only a modest experimental plant exists in the Bay of Fundy region. Installed in 1984 and located in the Annapolis River estuary, this small unit (20 MW) uses a "Straflo" combined turbine-generator to extract energy on an ebb tide, using a tidal range of 4.5 to 10.0 m. It may ultimately be the pilot for a vastly more ambitious undertaking to harness the great tidal ranges of the Minas Basin. In any event the construction of barrages in tidal waters is a formidable assignment. At La Rance, the French built the power units (total 250 MW) for the plant under dry conditions by placing cofferdams part way across the Rance estuary (Table 17). The placement of the cofferdams at La Rance succeeded, but not without a few tense moments. The relatively small power unit (800 kW) of the Russian plant was built into a floating caisson, 36 m long and 15.35 m high, which was then towed to the site and placed on a prepared bed. To smooth this bed the Russians sent some divers to the bottom equipped with hand rakes. It is extremely doubtful that such a procedure could be used in Fundy waters. A submerged tide gauge held down by pieces of railway track was placed in the upper portion of Cumberland Basin on 21

May, 1978, in 12 m of water. The current carried it away, and it was never relocated despite a thorough search.

Closing off parts of estuaries in the upper reaches of the Bay of Fundy would be a complicated undertaking, comparable but more difficult than the massive works carried out for the Deltaworks in The Netherlands. The latter are carried out through the cooperation of government personnel working together with contractors and a labour force experienced in this sort of work for many decades. The Deltaworks actually began with the construction of the enclosure dam and the first polder of the Zuiderzeeworks in 1927. Before that, the best scientific minds (among them H.A. Lorentz, Einstein's mentor) studied the implications of the closure of the Zuiderzee. The practical knowledge gathered during operations on both the Zuiderzee-and Deltaworks have established that undertakings of such magnitude require a sound logistical base in order to guarantee success. Planning a tidal power facility is not just a matter of placing a line on often outdated maps, and launching a public relations campaign. It involves plans that incorporate basic facilities such as sheltering harbours, and requires a sound infrastructure for constructing the facilities. Within the rigorous timetable ordained by the unforgiving tides, many new techniques would need to be developed and perfected.

"Fundy Tidal Power – Update '82" (Baker 1982) stated, among other conclusions, that: "Significant reductions in overall cost of a tidal power plant can be achieved by shortening the construction period and that should be one of the objectives of definitive design" (Baker 1982). In order to reach this objective it would be imperative that labour peace is guaranteed during the construction period. The "Update" also calls for the construction of 50 sluiceways and 64 turbine caissons, each 59 m long, 39 m wide and 46.25 m high, to be towed and placed on mattresses. This latter manoeuvre is an extremely delicate operation to be carried out during the periods of slack tide with split second precision, and in very close proximity of previously placed caissons. Any error of judgement will result in damaging collisions or time-consuming strandings of caissons. The construction and transportation of these 16-storey-high structures would require the ultimate of technical know-how. From the human perspective, these structures would be enormous, but in fact they are as delicate as oversized aquariums. They will have to be placed on platforms that will support the caissons evenly; otherwise internal stresses can play havoc with the structures and their contained expensive turbines or sluice gates. The successful construction and emplacement of such platforms would be a colossal engineering feat.

Table 17. Summary of tidal power generating capabilities of various sites

Petitcodiac and Memramcook – 1945	
Tidal Range	6.4 to 15.8 m
High Basin, Petitcodiac	31 km^2
Low Basin, Memramcook	5.6 km^2
Channel width	2650 m
30 generators at 9 MW each; 150 MW continuous power is typical	
Passamaquoddy – 1963	
Tidal Range	4 to 7.9 m
High Basin, Passamaquoddy	262 km^2
Low Basin, Cobscook	106 km^2
100 generators at 10 MW each	
La Rance – 1967	
Tidal Range	5.3 to 13.5 m
Basin Area	22 km^2 at high tide
Channel width	750 m
24 generators at 10 MW each; double effect with pumping at extremes	
Cumberland Basin – 1977	
Tidal Range	8 to 13 m
Basin Area	119 km^2 at mean level
Channel width	2560 m
37 generators at 31 MW each; single effect, falling tide	
Annapolis Royal – 1983	
Tidal Range	4.5 to 10 m
One generator at 20 MW; single effect, falling tide	

8. Ice Phenomena in a Bay of Fundy Estuary

8.1. WINTER CONDITIONS: A SHORT CASE HISTORY

The transition from fall to winter in the Bay of Fundy is a time of stark contrasts. Huge amounts of ice can be formed in a few days of heavy frost. As we shall see, this can rapidly bring about dramatic change in the character of tidal estuaries in the Bay of Fundy (Jennings *et al.* 1993). On Wednesday, 10 December, 1980, the Sun was out, the wind was light, and the temperature hovered about freezing on the marshes bordering Cumberland basin (Fig. 43). No snow was on the ground and not a speck of ice in the estuary. A survey of ice conditions in the area, planned for the coming winter, was about to begin. The plan called for surveys on foot, on skis, and by helicopter throughout the period that ice would be present in the Bay. That day scientists from the Bedford Institute of Oceanography would be inspecting sites that the senior author had volunteered to visit during the winter.

By the following morning, as the temperature fell, the weather had changed significantly. On Saturday, 13 December, it was so cold and windy that it was dangerous to be out on the marsh alone. However on Sunday, 14 December, the Sun appeared again and conditions moderated. Five centimetres of snow covered the ground. In the morning, as the tide ebbed past Lusby marsh (LM on Fig. 43), one third of the ebb channel was covered with ice moving in the outside bend of the basin. Already formed were most types of ice common here in winter.

The drifting ice was mainly slush, or *frazil ice*, formed in open water areas termed "ice factories" (Knight and Dalrymple 1976), and made up of an unconsolidated mixture of needle-like ice crystals and sediment-laden water. There was also a good representation of pan ice, and cake ice. Pan ice, also present, is formed from accumulations of slush ice, frozen together in flat slabs up to 15 cm thick. Cake ice is considerably thicker, and probably forms as pan ice is jostled in fast-moving, ice-packed water. On its perimeter, cake ice picks up slush ice, creating an elevated ridge, or levee. The resulting basin-shaped central part can at least temporarily, hold silt-laden water. However the water usually seeps through the porous ridge leaving the silt behind. Collisions with other ice cakes evidently round the undersides of the cakes. Floating by too were a few scattered blocks of composite ice protruding 0.5 m and higher above the surrounding ice. On 14 December the only type of ice not yet in evidence was floe ice, normally formed where salinity and tidal energy are greatly reduced. Floe ice consists of frozen assemblages of all other types of floating ice, 50 to 100 m in diameter, that move restlessly with the tides, up and down the estuaries.

Following Desplanque and Bray (1986), the foreshore is here divided into three subzones (see also Fig. 44). The upper subzone is the vegetated high marsh that, in the upper reaches of the Bay of Fundy, is approximately 1.2 m below the highest levels that tides normally reach. Dominated by river-related processes, this subzone is not often covered with tidal water. During some winters, tides do not reach this level, in which case the high marsh escapes ice deposition (Dionne 1989). However, frozen crust, another major type of ice also present on 14 December, usually forms on the surface of the intertidal sediment. This "shorefast ice" results from the combined action of downward-freezing pore water, upward accretion of precipitation, run-off and, depending on the season, sea water (see also Desplanque and Mossman 1998b).

The landward limit of the high marsh is formed by dykes, uplands, or in the case of extensive salt marshes, freshwater bogs. On the seaward side a vertical scarp 1 m or more high separates high marsh from the middle subzone. In sheltered sections of the shoreline the upper portion of the middle subzone may be covered during the summer by *Spartina alterniflora* (low marsh) and algae. Where rock is present seaweed may cling to it. Slippery mud, underlain by semi-consolidated material of similar grain size, covers the lower sections. The middle subzone has a relatively gentle gradient (approximately a 1 m drop in about 50 m), and its lower limit is also a scarp (Fig. 44) although not as high as the upper scarp. The lower subzone slopes toward the edge of the ebb channel, forming the *thalweg* (the median line of the channel) in Cumberland Basin.

On 14 December, 1980, the lower half of the middle zone was completely covered with cake and pan ice. Several centimetres thickness of silt had accumulated on some of the cake ice. On the upper half, a scattering of ice indicated the height of the tide during the preceding few days. The foot of the upper scarp had not been reached by the ice. In some places the lower subzone was covered with a crust of glazed ice beneath which water flowed toward the lower edge of the zone; in others, the ground was bare and unfrozen.

Several ice blocks stranded in the middle zone were constructed of 4 or 5 layers of ice of differing structure. Most layers were parallel, but some were oriented up to 45° relative to the others. The blocks, from 1 to 1.5 m high and 3 m square, contained much silt. However their buoyancy was very high because of the numerous air pockets. These sizeable blocks must have formed during the preceding three days because, as noted, ice was not present on 10 December.

During this three day period, the tides had not been large by Bay of Fundy standards; they ranged from a predicted 7.8 m + CD at Saint John on 10 December, to 7.3 m + CD on 14 and 15 December. However from this day on the tides became stronger, reaching a predicted height of 8.5 m + CD on 22 December. This semi-monthly inequality of 1.2 m at Saint John translates into an inequality of 2.0 m or more in Cumberland basin.

The weather remained cold. On 21 December it was unsafe

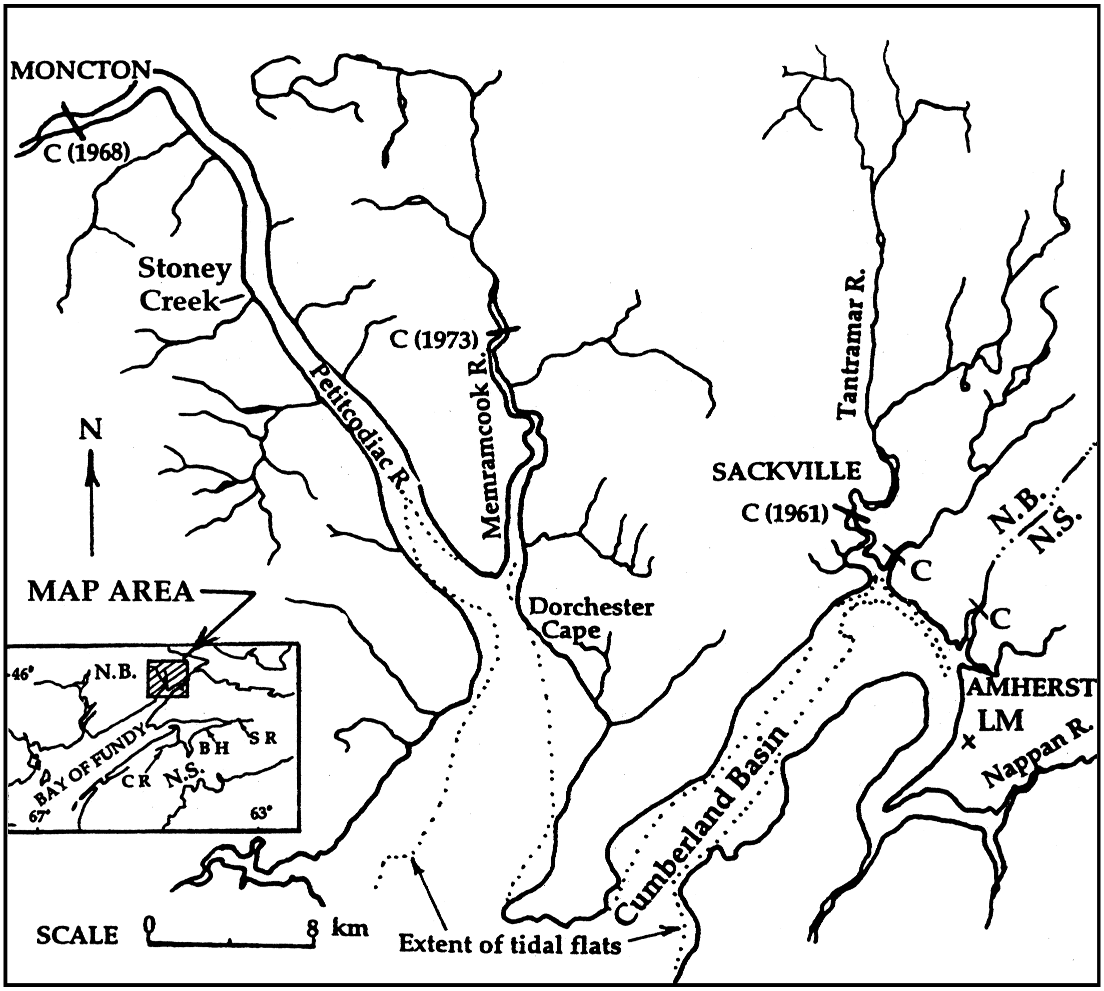


Fig. 43 Index map of the northernmost portion of the Bay of Fundy shows various estuaries. Note too, the locations of causeways (C) across various rivers. LM marks the location of Lusby marsh. Inset shows New Brunswick (N.B.) and Nova Scotia (N.S.); location of Cornwallis River (CR), Burntcoat Head (BH), and the Shubenacadie River (SR).

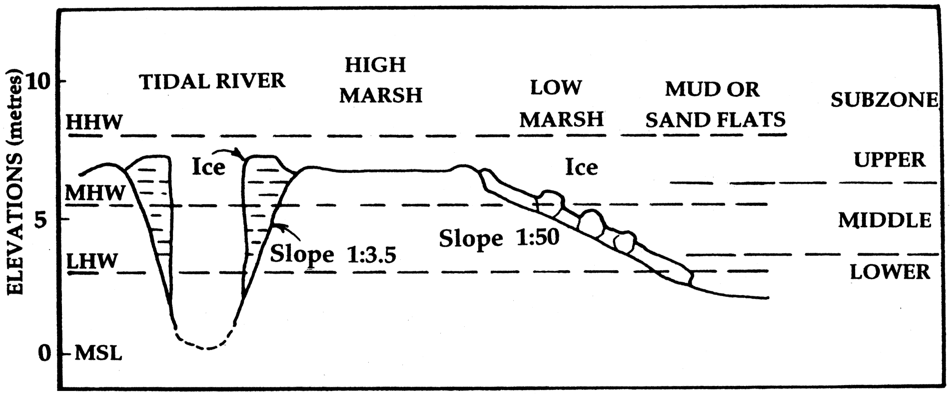


Fig. 44 Different types of shorefast ice along tidal rivers and the upper edge of tidal flats. High marsh areas can be invaded by sea ice only during winters of extreme tides. Lower edge of shorefast ice bordering tidal flats may be floated at high tide. Slopes (vertical:horizontal), and generalized subzones (lower, middle and upper) as indicated. Modified after Desplanque and Bray (1986).

to visit the site, but on 23 December we observed the effect of the increasing strength of the tides on the accumulation of shorefast ice forming along the shoreline in the zone between neap and spring High Waters. The middle subzone of the foreshore was now filled with a thick layer of chocolate-coloured ice to 0.3 m below the level of the high marsh. It was impossible to reach the lower subzone because ice-covered crevasses between the cakes made the going extremely hazardous. Gradually the rising tide submerged the lower subzone and all types of floating ice covered the basin. Pan ice penetrated marsh creeks, becoming stranded on their banks.

Flat pan ice is commonly deposited on earlier-formed pan ice ferried in on weaker tides to freeze onto the banks. On higher parts of the foreshore stranded ice is left longer exposed to freezing air temperatures, and is more likely to become anchored to the banks (Sweet 1967). Commonly, ice may become bonded so strongly to a clay or silt substrate that it will not refloat when covered by a higher tide. In contrast, the connection between ice stranded on gravel or loose rock is rather more fragile. Sheet ice formed in the lower subzone of the foreshore moves up and down with the tides because the substrate cannot freeze during the shorter exposure to supercooled air. This vertical movement of the sheet ice creates a bellows-like action between the ice and soft mud, promoting vigorous erosion.

8.2. THE PHENOMENON OF ICE WALLS

In the upper reaches of tidal estuaries, sea water can bring in ice that gradually builds up high vertical walls. Forced into the ever-narrowing sections of the estuary by a sort of ratchet movement, the ice is unable to exit. Initially, ice walls are rather porous and irregularly-shaped accumulations of ice. However, passing tides charged with floating ice cakes smooth off the rough edges, filling the pores and leaving a film of silt-laden water to freeze into a smooth surface layer of ice. Before long the trapezoidal cross-sections of tidal creeks, with side slopes of approximately 1:3.5, are transformed into rectangular channels of much smaller cross-sectional area (Gordon and Desplanque 1981). This in turn reduces the tidal prism and eventually also the flow rate of tide in the estuary (see Fig. 45).

During winter, ice walls 5 m high can build up in a week or less. Typically, ice forms a levee that is higher beside open

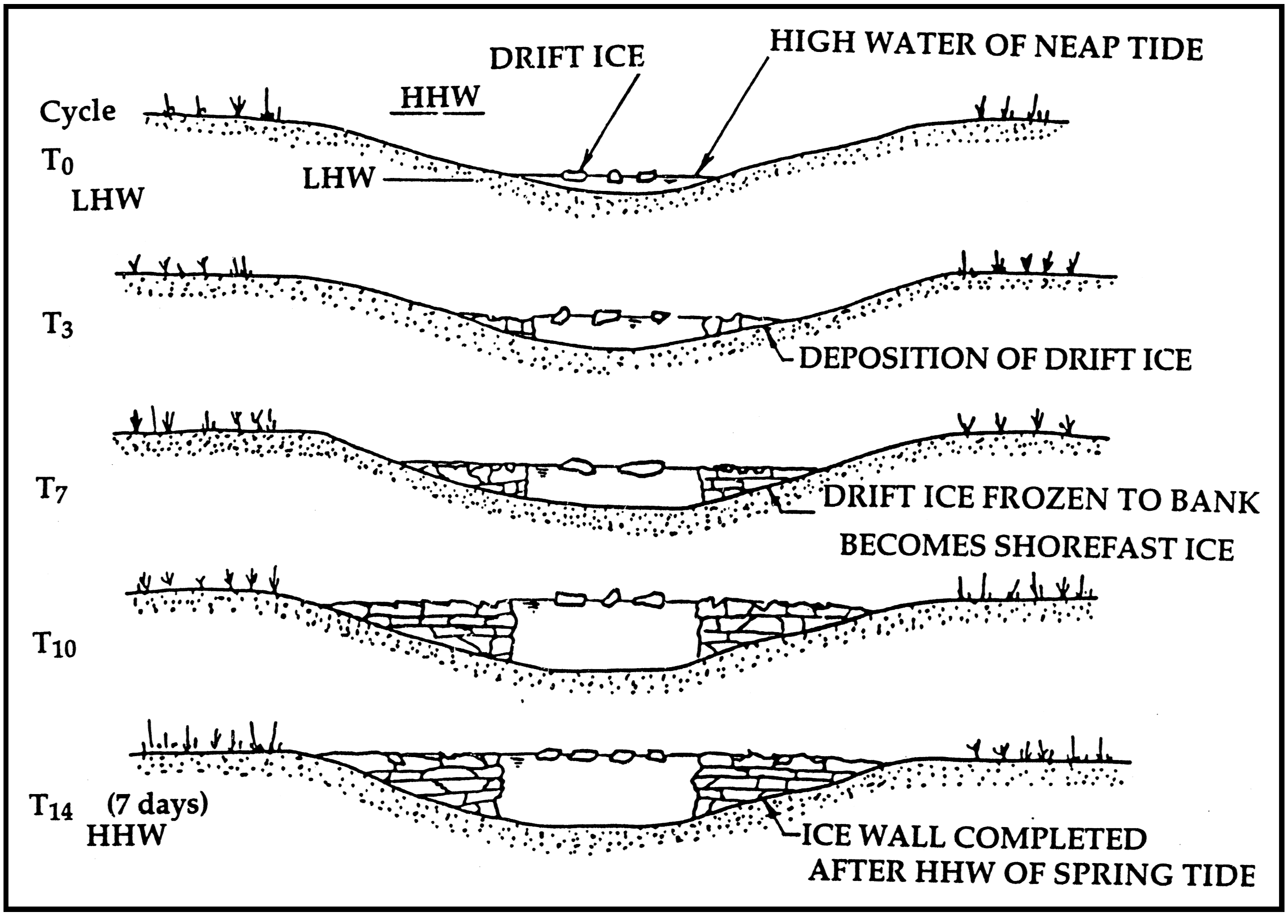


Fig. 45 **Diagram showing development of shorefast ice in forming an ice wall in a cross-section of a Fundy estuary delineated at day 1 (T_0) by High Water associated with a neap tide, during periods of freezing temperatures, and at day 7 (T_{14}) by High Water associated with a spring tide. After Desplanque and Bray (1986).**

Fig. 46 Memramcook River at College Bridge, N.B., spring 1959 (see Fig. 43), shortly before noon. Note how bridge piers influence movement of ice, incoming on the tide. A natural levee, formed by ice, is commonly higher near open channels than near the banks, a condition which can lead to flooding of the more inland shore ice. Note that this and following numbered photographs were taken for the Government of Canada (DREE) by Clifford Banks, and are used with permission; this is Photograph # 359-137.

Fig. 47 Downstream of College Bridge, early morning, several hours before photo taken at location shown in Fig. 46. Snow that had fallen since previous High Water partly obscures the High Water mark. There are indications of subsidence of part of the ice wall. Photograph #359-205.

Fig. 48 Photo from same location as Fig. 47, several days later. The ice wall begins to deteriorate. Photograph 459-1.

water than toward the bank of a tidal creek (see Figs. 46, 47, and 48). These figures illustrate that impressive ice walls can form even in years of moderate tides. The foot of an ice wall tends to be slightly lower than the level reached by the lowest High Waters occurring during the frost period. Most of the ice becomes stranded shortly after High Water. Slack water intervals in tidal creeks are brief, to the point of non-existence. They occur after the water level has dropped following High Water. At High Water the water continues to move into the estuary on its own inertia. This process delays filling of the upper parts of the estuary with tidal water. Thus at High Water the ice is still moving in, to become stranded shortly afterward. Ice that is lifted onto the top of the banks or onto previously stranded ice will likewise be left high and dry when the ebb sets in. Before the next High Water the chances are good that this ice will become solidly frozen to the underlying base and will not be refloated. If it does manage to break loose, this will occur on the rising tide and stranding will occur at some point further into the estuary. The process sounds mundane perhaps, but in actual fact it is a most remarkable exercise in ice block gymnastics. The performance seems surreal because the delayed release of ice blocks from the substrate beneath the rising tidal waters causes them to be released by buoyancy, as if possessed of life.

8.3. ASTRONOMICAL CYCLES AND ICE BUILD-UP

Ice build-up will be heavier during some winters than in others because of tidal conditions (see Fig. 49, Table 18). Peaks of perigean tides and spring tides coincide in cycles of 206 days. Two of these cycles last 412 days with the result that from year to year the especially strong tides occur 47 days later than in the previous year (412 – 365). During the first half of the 206-day cycle, the difference in height between neap tide and spring tide is decreasing, or below average, allowing a lesser ice wall build-up. Conversely, during the second half of the cycle, tides will gradually rise to higher levels during the week before the perigean tides. One of the key ingredients in heavy ice build-up is thus the timing of the greatest difference between neap tide levels and spring tide levels. This occurs one or two months before the perigean and spring tides combine to form the strongest tide of the cycle. Thus, when the latter half of the 206-day cycle occurs during the frost period between December and the end of March, one can expect the greatest build-up of ice walls. The formation of high ice walls in the Bay of Fundy was first recorded by Henry Y. Hind on or near 25 April, 1875 (Hind 1875). One hundred days earlier, the spring tide will have been at its minimum. Thus, the latter half of the 206-day cycle fell during the first period allowing ice to accumulate on the strand a month early, with accumulation probably peaking toward the end of April.

Naturally, the ice walls on either side of an estuary converge inland. Near the upper end of the estuary they will almost touch, leaving a strongly reduced channel in which freshwater runoff takes over the main role in channel-shaping. The drastic reduction in cross-sectional area can lead to flooding during a sudden winter thaw or spring break-up. The channel may then become choked with freshwater runoff, and/or ice.

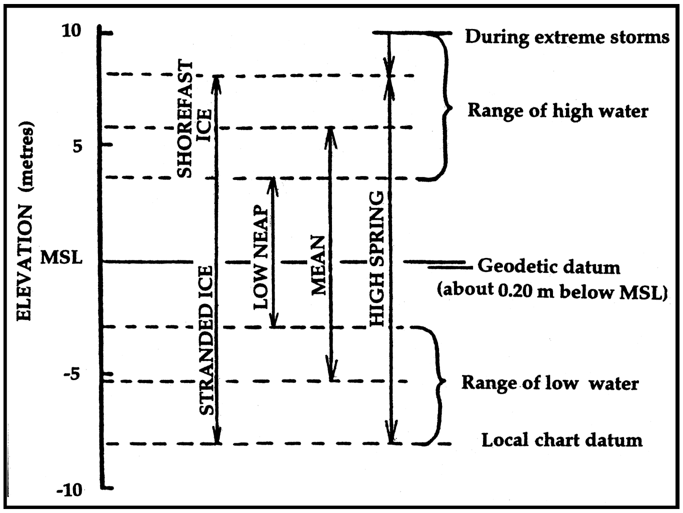


Fig. 49 Some tidal characteristics related to the ice regime in northeastern estuaries of the Bay of Fundy. Ranges and variation of tidal amplitude, Shepody Bay, showing the range over which particular types of ice occur.

Table 18. Summary characteristics of major constituents of tidal cycles in upper sections of the Bay of Fundy

Cycle	Period	Approx. tidal range
1. Diurnal cycle due to relation of Moon to Earth	0.517 days (12 hr 25 min)	11.0 m
2. Spring/neap cycle	14.77 days	13.5 m
3. Perigee/apogee	27.55 days	14.5 m
4. 206 day cycle due to spring/neap, and perigee/apogee cycles	206.0 days	15.5 m
5. Saros cycle (last peaked in 1994-1995)	18.03 years	16.0 m

Certain rivers, such as the Salmon River near Truro, N.S., seem more prone than others to such flooding.

8.4. HAZARDS VERSUS BENEFITS OF ICE WALLS

The development of ice walls can contribute to disastrous problems in tidal waters. In 1965 a fertilizer plant was built at Dorchester Cape, N.B., near the confluence of the Memramcook and Petitcodiac River estuaries (see Fig. 43). In order to handle the bulk material to and from the plant, a wharf was constructed nearby. Because of the large local tides, a $2.5 million floating dock was constructed in the form of a 25 m × 90 m × 7 m concrete caisson connected to a wharf and concrete platform on shore by means of a bridge and connecting arms. At this location (see also Fig. 3) the average range of the tide is over 11 m, increased during large tides to more than 15 m. Since trucks had to move over the bridge the slope needed to be maintained within certain limits. Hence the distance between platform and caisson was substantial. Also, the tidal channel was dredged, allowing the caisson and ships tied to it to move freely up and down with the tide.

The facility, named the Port of Moncton, was officially opened on 24 November. Winter followed the departure of the first ship. An ice wall developed along the shoreline, and worse, between the platform and the caisson beneath the caisson arms. When this wall became sufficiently high and strong, it blocked the free movement of the connecting arm and bridge. The bridge lifted out of the water, the connectors buckled and broke, and the caisson drifted away, stranding on a nearby silt flat. The entire operation was subsequently shut down. Ironically, predicted and observed tides for November, 1965 were low, so that ice conditions might have been a lot worse!

What are the ecological implications of ice in the upper reaches of the Bay? At one time it was believed that ice moving from the high marsh during winter was the main agent responsible for transporting organic matter from the marsh into the Bay. However during most winters, ice is unable to move onto the high marsh. Thus the organic detritus of high marsh vegetation survives until spring only to disappear beneath fresh vegetation in the same manner as non-cut grasses on upland meadows, presumably by microbial decomposition.

Decaying high marsh vegetation is commonly deposited along the dykes in thick accumulations (Nova Scotia Department of Agriculture and Marketing 1987). Hydraulic conditions on the marsh are such that they inhibit most if not all seaward movement of organic debris; flow is too gradual at these shallow depths to accomplish transport.

On the low marsh, exposed vegetation is crushed and frozen into blocks of ice. Subsequently these blocks may be lifted by the spring tide, pulling the encased vegetation from the marsh. Removed to higher elevations they will remain stranded until the ice thaws, leaving the vegetation behind. In tidal rivers, ice walls begin to collapse by the end of March and most ice disappears except for shorefast ice that may persist until late April (see Figs. 50, 51). Stranding of large blocks of composite ice on the mud flats, acting in concert with the bellows action of sheet ice hinged to the shoreline, may cause the complete reworking of the soil under the sheet ice during the late winter and early spring. In late spring some tidal flats resemble plowed fields with great scars left by chunks of moving ice. Any form of life in this mudflat ecosystem survives only under a great deal of stress (Gordon *et al.* 1985). Macrofaunal diversity is very low. In addition to organic secretions of diatoms, most of the productive biomass derives from three species (Hicklin *et al.* 1980): a bivalve (*Macoma balthica*), a polychaete (*Heteromastus filiformis*) and an amphipod (*Corophium volutator*). The amphipod, so important to migrating bird life in the Bay, is widely distributed over the mudflats. Its survival in winter is doubtless predicated by its ability to burrow well beneath the zone of scour and erosion. Since ice scouring is most intense on the outer portions of mudflats, the role of shorefast ice may afford an important protection to these species in the inner several hundred metres of mudflats at the mouths of estuaries. *Corophium volutator* may also occur on exposed tidal flats with no ice.

With approaching spring, flows of freshwater and tidal water progressively undercut the basal portion of ice walls and ice blocks. In places the ice is sculpted into dark-coloured, ephemeral toadstool-shaped formations charged with concentrations

Fig. 50 **Tantramar River at the Middle Marsh Road, Sackville, N.B., 22 March, 1954. Here, the ice wall formed in January and had some ice cakes deposited on top of it during the high tides in February. Shorefast ice is starting to break up. The rough sides of the ice wall show that not much water is reaching it during High Water. Fundy tides were relatively low during 1954. Photograph #354-3.**

Fig. 51 **Tantramar River between the C.B.C. transmitter and Middle March Road, about 2 km downstream from location shown in Fig. 50, 22 March, 1954. The tide is able to enter this section of the river (closed off by control gates about 1960) where an incomplete ice wall is formed. Ice block in right foreground is a conglomerate of many smaller ones. Left of centre, an ice block is stranded on top of another one, and frozen to it. Silt indicates that the ice was overtopped by the tide. Photograph #354-4.**

of estuarine mud as high as 18g per kg (i.e., 18 wt %) mud. By early April the thinner ice will have disappeared, but ice walls may persist until month's end (Fig. 52). At their base, huge accumulations of silt occur in sections sheltered from strong currents. It is remarkable that the ice fields are in the same locations where silt built up after construction of the Petitcodiac River causeway in 1968. Causeway construction promotes silt accumulation, with concomitant depth reduction of tidal rivers, and dire results for much aquatic life (Daborn and Dadswell 1988). With hindsight it can be seen that the river and its ice accumulations act like an enormous hydraulic sluice. Thus, whereas ice walls and associated phenomena may prove hazardous to man-made constructions they serve very important natural purposes. In the case of ice walls, their smoothness resists further narrowing of the channel, increases the net ebb and river flushing currents, maintains river depth, increases the surface slope seaward, forces the salinity intrusion seaward, and obstructs massive influx of ice from the estuary mouth.

8.5. ICE-RELATED PROBLEMS IN ESTUARIES OF THE BAY OF FUNDY

There are many lessons to be learned from a consideration of winter conditions in a tidal regime as complex as that of the Bay of Fundy. Intertidal ice is an extremely active agent in diverse environmental processes, both physical and biological, in this macrotidal region.

From a strictly engineering perspective, the sequence of tides, temperatures, and wind velocities must be carefully evaluated in estuaries in northern regions subjected to a large tidal range. Floating structures attached to an estuary bank are at risk due to build-up of ice walls. So too, are bridges, where ice build-up increases the size of bridge piers, resulting in reduced cross-sectional area at the crossing (Figs. 53, 54). Construction designed to control flooding of marshlands must consider the downstream channel changes from trapezoidal to rectangular as ice factories swing into production. Shorefast ice can greatly inhibit the workings of one-way drainage devices, whether mechanical (flap gates) or electrical (gate slots), on hydraulic structures that are installed without due regard to winter conditions.

Concerning megaprojects like tidal power production, it is quite certain that a tidal power project would result in major changes in the dynamics and distribution of ice in an estuary. Reduction of tidal energy would promote water column stratification, which would extend the ice season. Sheet ice could expand near tidal rivers and by excluding extreme tides, the development of shorefast ice would be retarded. Not least, accumulation of drift ice at the barrage would need to be considered at the early design stage.

February is usually the time of heaviest ice build-up. Ice jams (dams) are most likely to occur in the upper part of an estuary during a period of low temperatures and spring tides. Conditions in the Bay of Fundy will be greatly exacerbated by strong, prevailing southerly to southeasterly winds that might coincide with a rapid thaw and heavy rains. Doubtless the most important factor affecting intertidal ice conditions in the Bay of Fundy is the unusually high tides. This results in several conditions not commonly encountered in other regions. Thick ice walls may be unique to Fundy estuaries due to the pronounced variation in the elevation of High Water during the spring/neap cycle, and the prolific High Water stranding of drift ice. Also unique, as we have seen, is the substantial variation in elevation of extreme (extraordinary) tides over longer periods than the spring/neap cycle. This factor affects the extent to which shorefast ice develops, and the degree to which the high marsh areas are influenced by sea ice. Hind (1875, p. 193) elegantly described the behaviour of ice in the lower zone of a Fundy estuary: "The appearance of an estuary in the Bay of Fundy at any time in midwinter presents some singular and striking phenomena, which may contribute to our knowledge of the manner in which different agents have assisted in excavating this extraordinary bay, and are now engaged in extending its domains in some directions and reducing it in others." At the time, his concern was with the potential impact of ice on the Baie Verte canal, proposed to link Cumberland Basin to the Northumberland Strait. Although this project was never completed, various large scale construction projects and a multitude of smaller scale coastal management and development schemes will continue to merit quality time applied to the task of understanding the dynamics and environmental effects of intertidal ice.

Fig. 52 Petitcodiac River at Moncton, N.B. View southeast from Bore Park toward Dieppe, 11 March, 1959, shows extensive ice field in the river and the nearly vertical ice wall separating it from a secondary channel. Photograph #359-204.

Fig. 53 Tantramar River downstream of former Highway 2 Bridge, Sackville, N.B., 12 March, 1959. Note the coating of ice on bridge piers obstructing the flow of the tide. Some sheet ice has formed. Smaller ice blocks are stranded on top of larger ones. Photograph #359-203.

Fig. 54 Same location as Fig. 51, 8 April, 1959. The thaw set in on 30 March, enabling the tide to reach locations at higher elevations. Most of the ice coating is gone; some "toadstool" formations remain, showing that some ice remains bonded to the banks. Banks and ice are covered with a layer of silt. Photograph #459-3.

9. Sea-level Changes and Tidal Marshes

9.1. POSTGLACIAL SEA-LEVEL RISE

In the Bay of Fundy region changes to shorelines are due primarily to tidally-driven processes of erosion, and to changing sea level through geologic time (Shaw *et al.* 1994; Stea *et al.* 1998). Because of its economic importance, the rise in sea level since initiation of the last deglaciation about 15 000 years ago, is subject to intensive study. In eastern North America generally, and in the Bay of Fundy in particular, abundant and diverse lines of evidence indicate that regional differences in sea level reflect postglacial isostatic compensation. A vast literature exists on this subject and debate continues concerning a link between a possible accelerated sea-level rise in response to a global warming (Peltier 1999). Here we focus on the nature of the dynamic interaction between land and sea as evidenced by erosion and the Holocene history of sea-level change in the Bay of Fundy.

Topographical maps give the heights of mountains as measured from mean sea level (MSL). The same maps are also quite definite in showing the location of shorelines. This assumes that MSL is permanent and known with a great degree of accuracy. Unfortunately MSL is a rather elusive concept. It certainly is not at a permanent elevation. The landmasses are ever so slowly bobbing up and down, and the oceans are not always filled with the same volume of water. Tectonic and isostatic processes contribute to an uneven sea-level rise along coastlines.

The future duration of the current interglacial is uncertain. During glacial maxima, large portions of the continents ringing the Arctic Ocean were covered with massive sheets of ice. The largest accumulation of ice during the last glacial advance occurred 20 000 to 18 000 years ago. In North America this last glacial is called the Wisconsin glaciation, and in Europe, the Weichselian (or Würm). At that time, so much water was locked up in ice that sea level globally was 100–130 m below present MSL (Fig. 55). Across the Scotian Shelf, for example, this is indicated by a well-developed submarine terrace at a depth of 115–120 m (Fader *et al.* 1977). In the Bay of Fundy, however, the terrace occurs at a depth of 37 m, a feature of fundamental importance to the distribution of surficial sediments in the Bay (Fader 1989).

Centered over Hudson Bay, the Laurentide ice sheet blanketed most of Canada and extended far south of the Great Lakes. It crossed the Bay of Fundy and Gulf of Maine, approaching the edge of the continental shelf (van de Plassche 1991). End moraines and glacial outwash peripheral to the ice sheet, and even some drumlins that formed beneath it, now form many of the banks and shoals along the Maritime and New England coastlines (Grant 1989). The rate at which the ice has retreated since the last deglaciation began is quite astonishing considering that the nearest remnant is now located on Baffin Island about 3000 km north of the Bay of Fundy. Most melting was over by about 5000 years ago (Lambeck *et al.* 1990). As discussed below, the rate of retreat was irregular rather than constant, due in part to eustatic change and spatially varying crustal motions, even during the last 1000 years or so (Shaw and Ceman 1999; Shaw *et al.* 2002). The current rate of rise of relative sea level is therefore not necessarily tied to an anthropogenic greenhouse effect. In any case, the sea was able to return in the western sections of the Bay of Fundy about 13 000 years ago.

The weight of an ice sheet is sufficient to depress the Earth's crust significantly. Compensating for this downward movement, the land and sea bottom in front of the Laurentide ice sheet was forced up into a bulge more than 100 m high and 60 km wide. With retreat of the ice, recovery takes place and the peripheral bulges gradually disappear. However, this process requires thousands of years, and in the Maritimes the recovery is still going on (Fig. 55). Thus, bulges that may have formed small islands off the Nova Scotian coast and a land bridge between southwestern Nova Scotia and New England, have gradually undergone submergence together with large portions of the mainland itself. For example, at the peak of glaciation, Georges Bank was 40 to 50 m above sea level. Yet 11 000 years ago conditions were such as allowed growth of salt marsh upon it (Stea *et al.* 1994; 1998). About 12 500 years ago the area of Portland, Maine was at least 49 m below sea level, and the sea covered nearly 23% of that State as far as Bingham, presently 100 km from the sea. Coastal areas along the Bay of Fundy also emerged as the ice retreated. Well defined former sea level *stillstand* indicators, such as raised beaches and nicks eroded in shore-facing cliffs, set the marine limits about 42 m

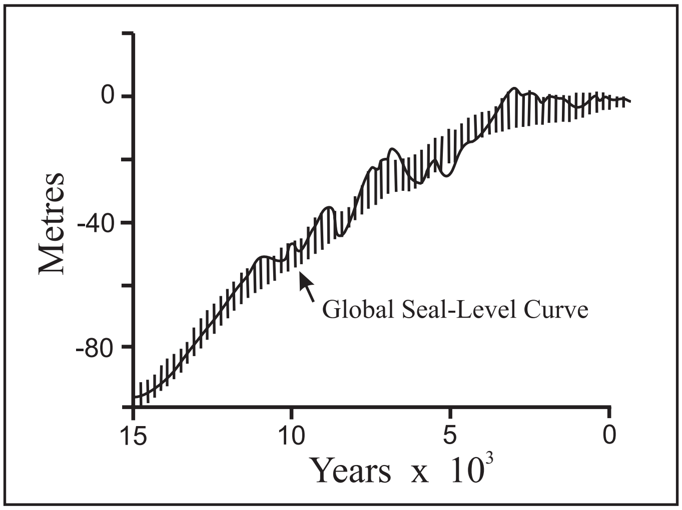


Fig. 55 Relatively short term, sea-level rise, from 15 000 years B.P. to the present. After Fairbridge (1987).

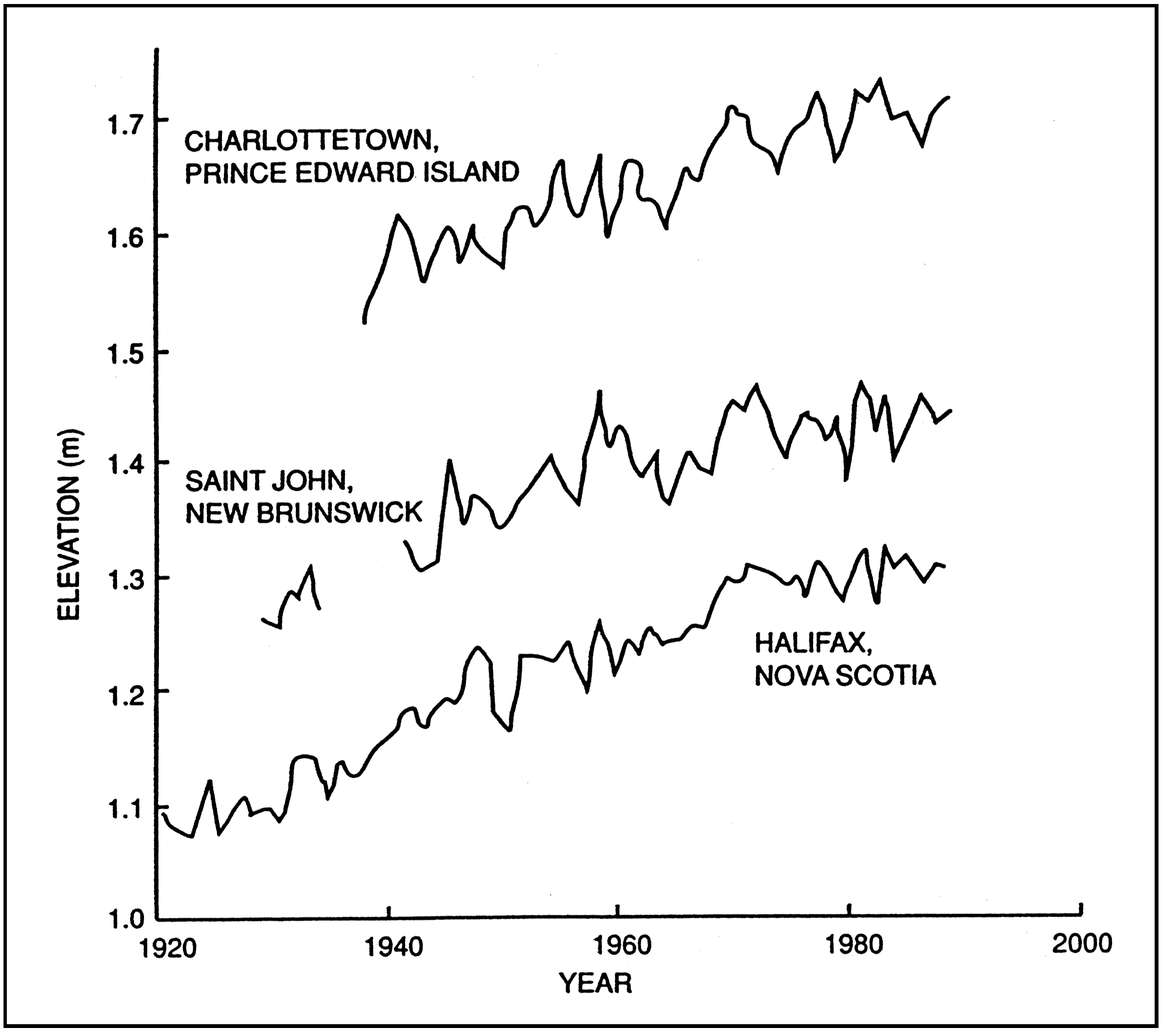


Fig. 56 Mean annual sea-level change (1920 through 1990) determined from tidal gauge records at tidal stations in the Atlantic Provinces. Modified from Hill *et al.* (1996).

above present MSL along Digby Neck and numerous other Bay of Fundy locations.

From 11 000 to 5000 years ago, the land rebounded from the depressing effect of the ice (Grant 1989), and rose faster than sea level. Although over several intervals the rebounding effect reportedly slowed (Scott and Collins 1996; Stea *et al.* 1998), allowing reversals to occur, the tendency has been for the rate of sea-level rise to overtake that of the land. Consequently, submergence has occurred at a faster rate than that due solely to eustatic rise. Eustatic rise in sea level amounts to about 10 m in the past 7000 years. It is important to note that the inferred eustatic rate of sea-level rise of about 1.3 mm/yr is occurring globally, regardless of the vertical motion of any particular shoreline (Schneider 1997). This is the direct consequence of thermal expansion of ocean water combined with additional water mass derived from shrinking glaciers. Thermal expansion of the oceans is in itself is a very important factor, and although estimates in the literature range between 0.5 and 2 m/°C, the best estimates indicate that a 1°C rise in ocean temperature would result in a rise in MSL of about 60 cm.

Presently, sea level is rising all along the Atlantic coast of North America, but nowhere more rapidly than in Nova Scotia (Scott and Stea 2000; Fig. 56). This rise has been continuous for the last 7000 years at a rate of 20–30 cm per century, accelerated between 5000 to 4000 yr BP when rates reached up to a metre per century (see Scott and Greenberg 1983). Tidal observations over the past 60 years confirm that the rate of rise remains about 3 mm/yr. For example, at Saint John, N.B., the measured rate is 3.6 mm/yr. At Halifax, sea level has risen 35 cm in the last 100 years; 20 cm is attributed to crustal subsidence, the balance is due to eustatic rise. Comparable rates occur along the coastline of the U.S.A. down to Florida. Along the northeast coast of Maine the rate exceeds 1 cm/yr. At places along the St Lawrence River estuary and the north shore of the Gulf of St Lawrence, the sea levels are not changing at present, although north of this line, for instance at Churchill, Manitoba, on Hudson Bay, land continues to rise relative to sea level (Hill *et al.* 1996).

While some areas were rebounding upward, other areas on the peripheral bulge were compensating for this movement and dropping in elevation (Scott *et al.* 1987). For example, at Lunenburg, N.S. sea level 7000 years ago was about 30 m lower than present, whereas peat that formed at the same time on what is now Georges Bank, can be dredged up from depths of 45 m.

During the last glacial maximum a glacier is believed to have occupied the Northeast Channel in the Gulf of Maine (see also section 4.3). The terminal moraine of this glacier may have served as a land bridge for the numerous species of plants that are native to southwestern Nova Scotia and southern New England but which are not found in the intervening coastal areas. Perhaps the Paleolithic people who settled in Nova Scotia 10 500 years ago used this land bridge to reach their hunting camps, the remains of one of which have been found at Debert, near Truro, N.S. (Grant 1975). Doubtless the existence of a land bridge restricted the free exchange of water between the Atlantic and the Gulf of Maine. The latter probably had a larger surface area than now because a large part of New England and the Maritimes was still covered with water. Today, with an average tide, about 300 km^3 of water flows in and out of the Gulf of Maine during a 12.4 hour period. If sea level was 30 m lower than today, the Northeast Channel in its present configuration would still have more than 75% of its cross-sectional area available for this flow. From a hydraulics point of view this restriction would have made little difference in the tidal characteristics of the area. However, if the channel was restricted by glacial material, and the surface area of the Gulf of Maine was much larger, tides of present strength could not possibly have been generated in the Gulf of Maine and the Bay of Fundy (Grant 1970).

9.2. MEMORIES OF THE MARSHES

Some very interesting features of tides and sea-level history in the Bay of Fundy, as discussed earlier (section 5.2), are substantiated in the geological record of tidal marshes. Marshes began to build up when tidal waters first covered coastal lands (Shaw *et al.* 1993). In the upper reaches of Cumberland Basin nearly 20 m of red clastic marine sediment have accumulated over the basal glacial till. Near Aulac, N.B., the marine sediments overlie a 6 m-thick layer of peat (Chalmers 1895). Given a compression ratio of about 3:1 or more for the vegetation to peat transition, the peat represents a formerly much thicker unit. The overlying silt will therefore also have been deposited at a higher elevation than it is now. Information from the drilling of wells has established that the lower limit of the clastic marine material is at a depth of 17–18 m below the present land surface. This sets the lower limit of that material at about 12 m below present MSL. Thus constrained, the marshes could have begun to form 6000 to 7000 years ago when tidal ranges and currents became large enough to move material from eroding coastlines and deposit it in the upper reaches of the Bay.

During the summers of 1980 and 1981 students of the Free University of Amsterdam studied the development of marshes in Cumberland Basin (Dekker and Van Huissteden 1982). About 600 boreholes were made with an average depth of 6 m and a maximum of 15.1 m (Noordijk and Pronk 1981). One borehole, reaching 8.9 m below present MSL, was still in red marine sediment. The texture and structure of this material are similar to those of recently deposited clastic layers. No indication was found that the tidal regime at the time of deposition was any less vigorous than now. Marshes that are formed in areas with weaker tides have generally a much greater content of organic material. The same is true of tidal marshes less often inundated with salt water.

As we shall see (section 9.6), tidal marshes along the upper reaches of the Bay of Fundy are generally built up to a level about 1.2 m lower than the level reached by the highest astronomically-caused tides. At this level, relatively few tides are able to cover the marsh with silt-laden water. Each additional layer of silt progressively decreases the potential for more build-up. Combined with tidal cycles, marsh build-up is intimately related to the rate of coastal submergence. When sea-level rise is slow, marsh build-up is also slow, resulting in fewer inundations and prevalence of freshwater conditions on the marsh, especially in areas farthest removed from the coast and main creeks. Plant growth in basin areas on the marsh will resemble fresh marsh vegetation and will leave more organic peat-like material (Shaw and Ceman 1999).

Studies of soil genesis in the marshes reveals that there are 5 to 7 layers of organic (plant) material at particular stratigraphic levels throughout the marsh areas. This has been interpreted in terms of successive periods of increased and decreased rates of relative sea-level rise (Lammers and De Haan 1980). This phenomenon indicates intermittent temporary slowdowns in the process of submergence. Similar observations have been made in coastal areas of the northeastern United States, and of France, Belgium and The Netherlands along the North Sea. If, as suspected, intermittent submergence is a world-wide phenomenon, postglacial sea-level rise is a punctuated process, not necessarily linked to an anthropogenic greenhouse effect as suggested by Van de Plassche *et al.* (1998).

Temporary slowdowns of coastal submergence means that certain sections of the coast with exposed bedrock were exposed longer than others to wave action and consequent erosion. Tidal action during such periods will have remained the same except that the eroded material could not have been deposited on the marshes to the same extent as previously, but must have been choking tidal estuaries and creeks. This would lead to even less tidal water reaching the upper marsh areas. However, when coastal submergence was renewed, this material was readily available to be moved on the marsh, leading to an interval of renewed and vigorous marsh growth (Grant 1975). The geological record preserved in the tidal marshes is quite explicit in this respect (Figs. 57A, 57B).

Initial rise in postglacial sea level is signalled by the presence of fossil forests at several locations in the upper reaches of the Bay of Fundy. Typically, fossil tree stumps are rooted in glacial till at the base of the marine sequence; remnants of younger fossil forests also exist at higher levels. Among the intertwined network of roots, the peat-like consistency of the original forest

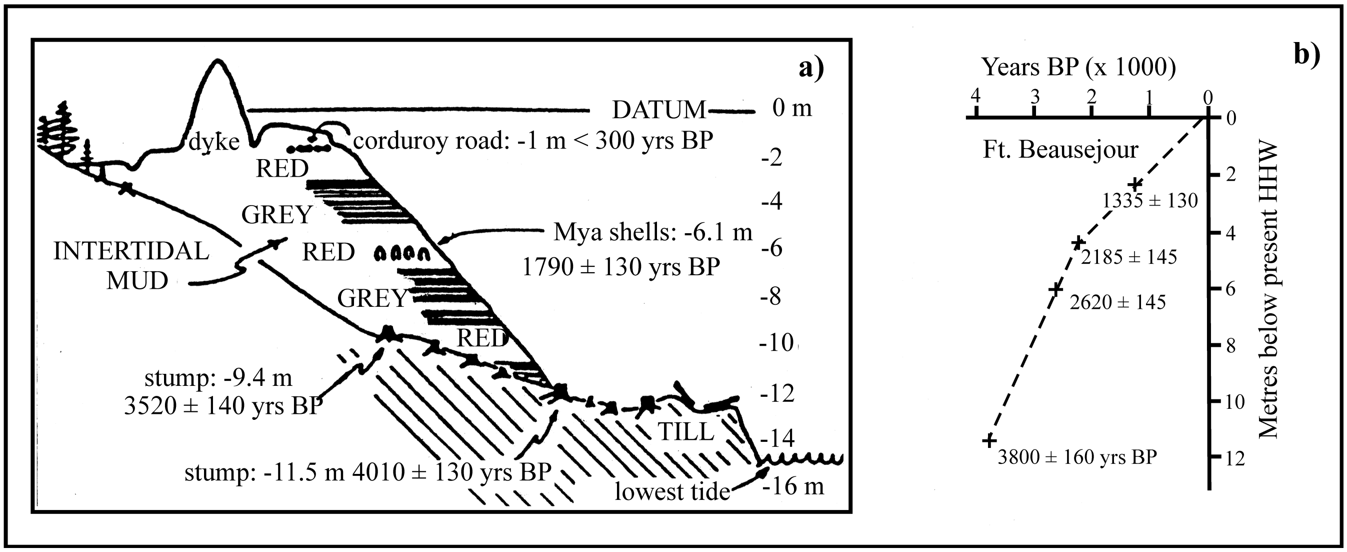


Fig. 57 **Sea-level change as evidenced in tidal deposits exposed at low tide on the shore at Fort Beausejour, N.B., at the head of the Cumberland Basin, in the Bay of Fundy. A) Section showing stumps and logs of buried forest at the base of the ca. 4000 yr succession covered by intertidal salt-marsh muds and peats. After Grant (1975). B) Relative sea-level curve for this locality established independently by Scott and Greenberg (1983).**

floor is commonly well preserved. A good example occurs on the shore near low tide at Fort Beausejour on the Nova Scotia-New Brunswick border (see Fig. 3). The levels at which these stumps occur is approximately 1.2 m below present MSL. In 1983 more than 70 stumps were exposed, some with a diameter of over 1.5 m. Although most disappeared during winter of that year, fresh examples, including several blow-downs, have since been exposed. Pollen analysis of the peat indicates that the forest was a moist, rather patchy mixed-forest with hemlock, pine and red maple, which until its destruction by the rising waters was not disturbed by salt water (Grant 1985; 1989). The tree stumps have been radiocarbon dated at 3300–3700 years BP. The maximum tidal range at Fort Beausejour is now about 15.6 m. Allowing 1.2 m for extraordinary storm tides, the stumps are approximately 10 m below the reach of a storm tide. This is compatible with a rate of submergence of about 3 mm/yr.

Although the section at Fort Beausejour is slumped, the relative sea-level curve obtained is reportedly comparable to those documented from several other locations around the Bay of Fundy (Scott and Greenberg 1983, p. 1556; see Fig. 57B). Most show a distinct break in the rate of sea-level rise at about 2500 BP.

9.3. COASTAL EROSION

The more than 11 000 km coastline of the Maritime Provinces exceeds a quarter the circumference of the Earth. Of this, the coastline along the Bay of Fundy totals about 608 km in New Brunswick, and 805 km in Nova Scotia. Along much of this length, erosion-prone sandstones and conglomerates are exposed; along other stretches, "harder" rocks, like the basalt along much of the Nova Scotia coastline adjacent to North Mountain, offer stiffer resistance. Most resistant are massive igneous rocks, metamorphic gneiss and quartzite, and limestone. All are present in this geologically complex region. Erosion-resistant rocks form the headlands and capes, and each coastal section responds in its own way to the erosive powers of the tidal waters. Thus, one encounters 100 m-high cliffs, low bluffs, beaches, mud flats, tidal marshes and sand spits at various places along the coast, depending on local geological and hydrographic conditions. The difference in tidal ranges also leads to significant differences in the erosion of littoral materials.

In general, beach slope gradients depend upon the cohesion of the shore and bank materials and on local wave energy levels. Coastlines consisting of hard rock, such as the North Mountain basalt, are not easily broken down by action of wave and weather. However where bedrock consists of relatively friable material such as sandstone, the slope of the foreshore is formed of debris dislodged by wave action from banks and cliffs along the shore. Here the slope of the foreshore is uniform and gently dropping from 1:10 to 1:200, depending on local conditions.

Due to continuing submergence, a small section of backshore, previously too high to have been exposed, becomes subject to wave action. Furthermore, the entire foreshore will be deepened so that wave energy will not be dissipated to the same extent in passing over it. Consequently wave attack on the shoreline becomes more vigorous. Equilibrium can be restored only if the foreshore is raised by debris removed from the freshly exposed backshore. Given the prevailing rate of coastal submergence and the evolution of the foreshore, the overall result is that the shoreline will have a tendency to retreat at a rate of 0.06 m to 0.8 m/yr depending on the slope of the foreshore and the resistance to erosion of shoreline materials. If the prevailing rate of submergence has been constant over the past 10 000 years, then sea level will have risen approximately 40 m since people first arrived on the shores of the Maritime Provinces, and 1.2 m since Père Pierre Baird described Saint John Harbour (see section 7.3).

The level of tidal waters lapping the shores of the Maritime Provinces is quite variable. Outside the Fundy region, tides are small, as in the western section of the Northumberland Strait (mean tidal range 0.6 m), or in the Bras d'Or Lakes, where the mean tidal range is 0.1 m. (The smallness of the range in the Bras d'Or Lakes can be brought home by the observation that changes in barometric pressure can cause differences in water levels of up to 0.3 m – Desplanque 1980; Petrie 1999.)

Wave energy is concentrated near the surface of the water. During high water the foreshore is covered by a significant depth of water and a far larger percentage of wave energy reaches the shoreline than when the tide is at low water. As noted earlier (see section 5.4.1), the zone of the shoreline near the water surface will be the most heavily subjected to wave action. Where water levels are rather constant, efforts at shore protection can be focussed in a limited zone. Conversely where macro-tides prevail, the problem of protection is complicated, and never more so than during perigean spring tides (Wood 1976).

9.4. COASTAL DEFENCE

In the Bay of Fundy tidal range in absolute figures is high. In the Minas Basin, tides have a mean range of 12 m and vary between 7 m and 16 m. Thus the zone in which the water surface meets the shoreline nearly 30% of the time varies between 2.8 m and 3.5 m above MSL during small tides and between 6.4 m and 8.0 m during large tides (Figs. 25, 26 and 27). This condition is clearly shown in terms of the amount of material eroded over a given tidal range. The exposed conglomeratic sedimentary rocks at Hopewell Cape, N.B., (see Fig. 29) provide an excellent example (Trenhaile *et al.* 1998; Desplanque and Mossman 2001a, 2001b). If any attempt is made to protect this sort of shoreline, then the zone requiring reinforcing needs to be at least 5 m high to have any effect. Attempts to protect shorelines are diverse: in many instances these prove to be expensive undertakings. Here we consider briefly one particular geological process all too often overlooked: the hydraulics of groundwater flow.

Due to density differences, fresh water can only move beneath the shoreline if it has an overpressure, because it needs to displace the heavier salt water. Should this overpressure dissipate because of friction and the pressures between salt and fresh waters become equal, then no transfer of water will take place. The plane where this situation exists is called the interface and its location is determined by the Ghyben-Herzberg ratio, which describes the static relationship of fresh groundwater and sea water in coastal areas (see Fig. 58).

Fresh water prevails on the land side of the interface, salt water on the sea side. Because fresh water loses pressure gradually, the interface rises in a seaward direction and interacts with the sea floor at the elevation where the column of salt water exerts a little less pressure than that of the fresh water moving along the interface. This means that the excess groundwater has a smaller zone of exit into a saltwater body than into a freshwater body, and is much more concentrated, typically in wet areas near the shoreline. This concentrated outflow may cause quicksand and other soil/rock- weakening conditions near the shoreline where wave erosion is focussed (Figs. 59A, 59B). Furthermore, the fresh water exiting near the shoreline will expand upon freezing, promoting more rapid weathering conditions than might otherwise be the case. Also, since this groundwater is likely to be warmer than the air temperature during winter, many freeze-thaw cycles are possible during that season. In order to inhibit erosion of a particular section of shoreline, care needs to be taken to avoid local build-ups of freshwater pressure. Protective cover employed to this end should not be so permeable as to allow material to be easily dislodged. Incorporation of an artificial filter beneath the protective layer should be considered.

Protection against coastal erosion is not only an expensive undertaking, but also involves high risks. The motto of a wise coastal engineer should read: "Be sure to put off to the future what you do not absolutely have to do tomorrow". The fight against coastal erosion is a struggle against strong and persistent forces in nature. Interaction of land and sea in the Bay of Fundy is a dynamic relationship. It is most obvious in recent cliff falls and in rapidly retreating bluffs as the sea advances inexorably and, at times of storm surge, disastrously. However, even on a decadal scale, continued sea-level rise is not always obvious upon cursory inspection. Measured in differences of several mm/yr, it is revealed in various sorts of tidal records, in bore hole data, and from radiometric and relative age data. At the head of the Bay of Fundy it takes the form of a startling paradox seen in the continued build-up of tidal marshes, as coastal submergence and erosion strive toward an equilibrium. Here, despite extensive dykelands, the marsh grows upward as sea level rises, yet recedes landward in the face of relentless erosion.

9.5. OVERVIEW OF MARSH TYPES

On a geologic timescale estuaries are ephemeral. The same is true for tidal marshes, because an extensive marsh occupies a natural estuary that has largely been infilled with sediment. A legacy of the ups and downs of the land surface in response to regional tectonics and climate, the system of tidal marshes extends around the Fundy shore, from Argyle and Chebogue south of Yarmouth, N.S., to the Musquash and Manawagonish marshes southeast of Saint John, N.B. (Fig. 60). They formed after the latest ice sheet retreated and mean sea level rose about 100 m to its present level, allowing tides to develop ranges and currents that could transport the sediment onto the marsh surfaces. Dyking was undertaken in the early 17th Century by the first French settlers, reclamation focusing along

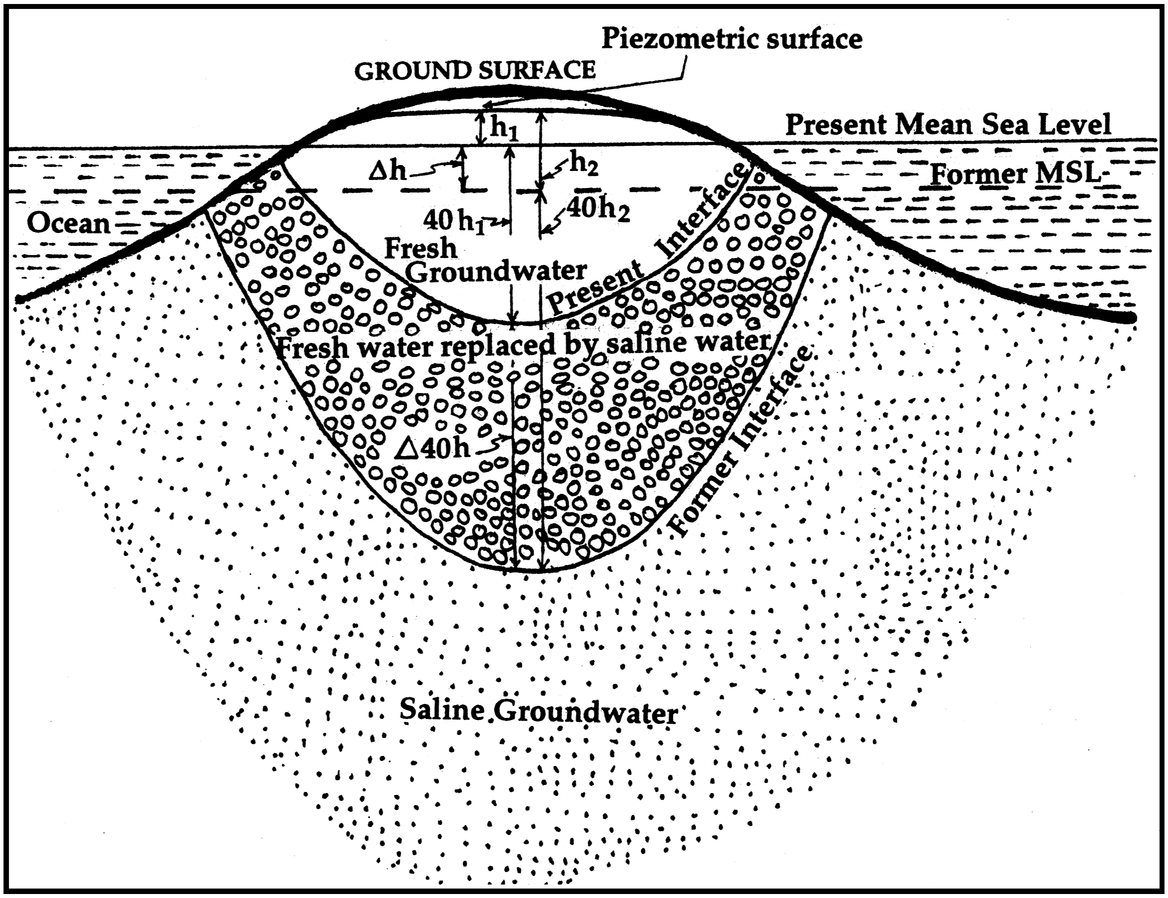


Fig. 58 **Idealized sketch shows the changing positions of the seawater/freshwater interface beneath a submergent nearshore island; h_1 and h_2 = respectively, the vertical distance between water table and the present MSL, and the vertical distance between the water table and the former MSL; 40h_1, and 40h_2 = respectively, the vertical distance between the present MSL and the present freshwater/seawater interface, and the vertical distance between the former MSL and the former freshwater/seawater interface.**

Cumberland Basin at the head of the Bay of Fundy. Johnson (1925) recognized three distinctly types of marshes along the eastern seaboard of North America:

1. *Coastal plain marsh.* This type occurs south of New Jersey and is abundant from Virginia to Georgia. Related in structure to Fundy type marsh (below), it is developed in a regime of tides of much less amplitude. For this reason the marshes are flooded by each tide. This is because the marshes can only build up to a certain vertical elevation below the highest local tides and the difference in height is large relative to the variation in the magnitudes of the local tides. However the soils have a higher organic matter content and a different surface aspect than those of the Fundy marsh.

2. *New England marsh.* Found from New Jersey to Maine, it differs from the Fundy marsh in that it is essentially a deposit of salt marsh peat with variable amounts of silt. The tides in this region too have a much smaller amplitude than those associated with the Fundy type. The Nova Scotia marshes in Yarmouth and Digby counties are of this type.

3. *Fundy type marsh.* These marshes are built in a regime of tides with large amplitude and strong tidal currents. The high silt-carrying capacity of the Bay of Fundy currents cause marshes to build up with mineral matter, which is removed from the bottom, the banks, and the exposed shorelines of the Bay. Incoming tide water has a reddish colour and a silt content up to 2%.

We define a salt marsh as a low-lying flat area of vegetated marine soils that is periodically flooded by saltwater inundations, generally caused by tides, to such a degree that only plants adapted to saline conditions can exist. This definition excludes: a) unvegetated tidal mud, sand flats and gravel bars; b) sand and shingle beaches; c) dunes; d) dykelands, being former salt marshes, presently protected from tidal inundations by dykes and aboiteaux; e) freshwater marshes that exist between the larger salt marshes and the upland areas. The distance from the sea is so large that salt water cannot reach this zone within the limited time period available even during the highest tides.

Since a marsh creek needs a certain area of marsh to maintain itself against sedimentation, there will be margins of salt marsh free of creeks, along uplands and dykes, and between creeks.

9.6. TIDAL FLOODING AND MARSH GROWTH

The Fundy-type marsh, although built in a regime of tides with large amplitude and strong tidal currents, rarely experiences overflow. Tides that rise high enough to flood marshes in the upper reaches of the Bay, move larger volumes of water at higher velocities and greater eroding and sediment-carrying capacities. During large tides, High Water at the mouth of the Bay may extend 2 m higher than High Water during small tides. In the upper reaches, this difference can exceed 4.5 m. However, in the upper reaches of the Bay of Fundy the sea floor is too high to allow a Low Water. Therefore, it is better to employ the terms "large" and "small" tides rather than refer to tidal range, the difference between Low and High Water.

In general, tidal marshes in the Bay of Fundy area are built up to a level 1.2 m lower than the highest astronomical tides. Thus, only large tides can reach marsh levels and only very large tides are able to cover the marshes. For instance, on average, only 52 tides per year (standard deviation, SD, of the variation in tidal occurrences = 12) will be able to reach above the level

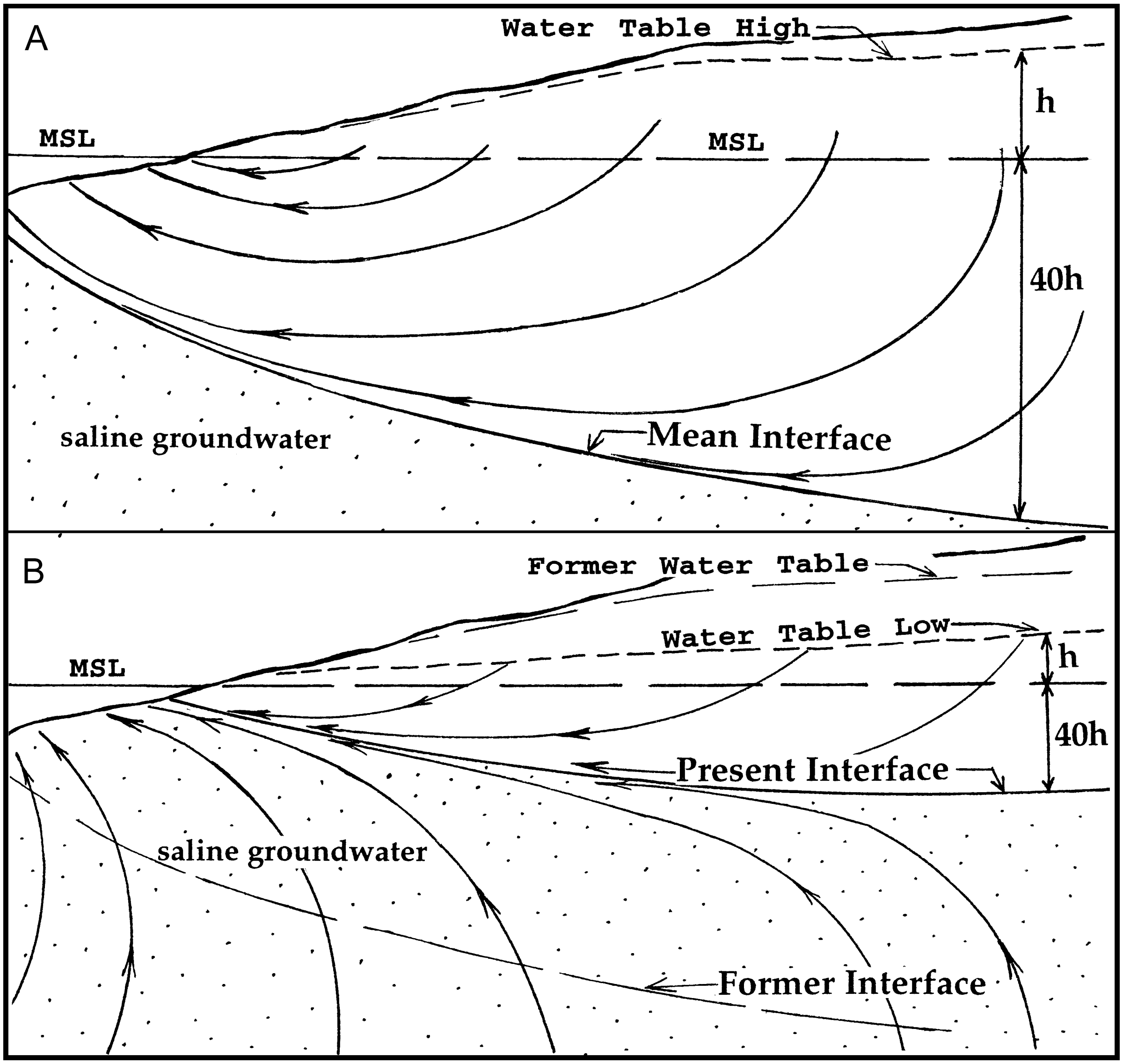


Fig. 59 Profiles show fresh groundwater encroaching on the foreshore. A) Water table is high, and fresh water moves onto the foreshore beneath the shoreline due to overpressure; soil/bedrock conditions are consequently weakened along the foreshore. B) Supposing that MSL is raised (or the water table is lowered by overpumping of the freshwater body), the interface between saltwater and fresh water moves shoreward. Saltwater incursion occurs, in part due to lack of freshwater overpressure. Arrows indicate hydraulic pressure flow lines; h_1, h_2, $40h_1$, $40h_2$, as in Fig. 58.

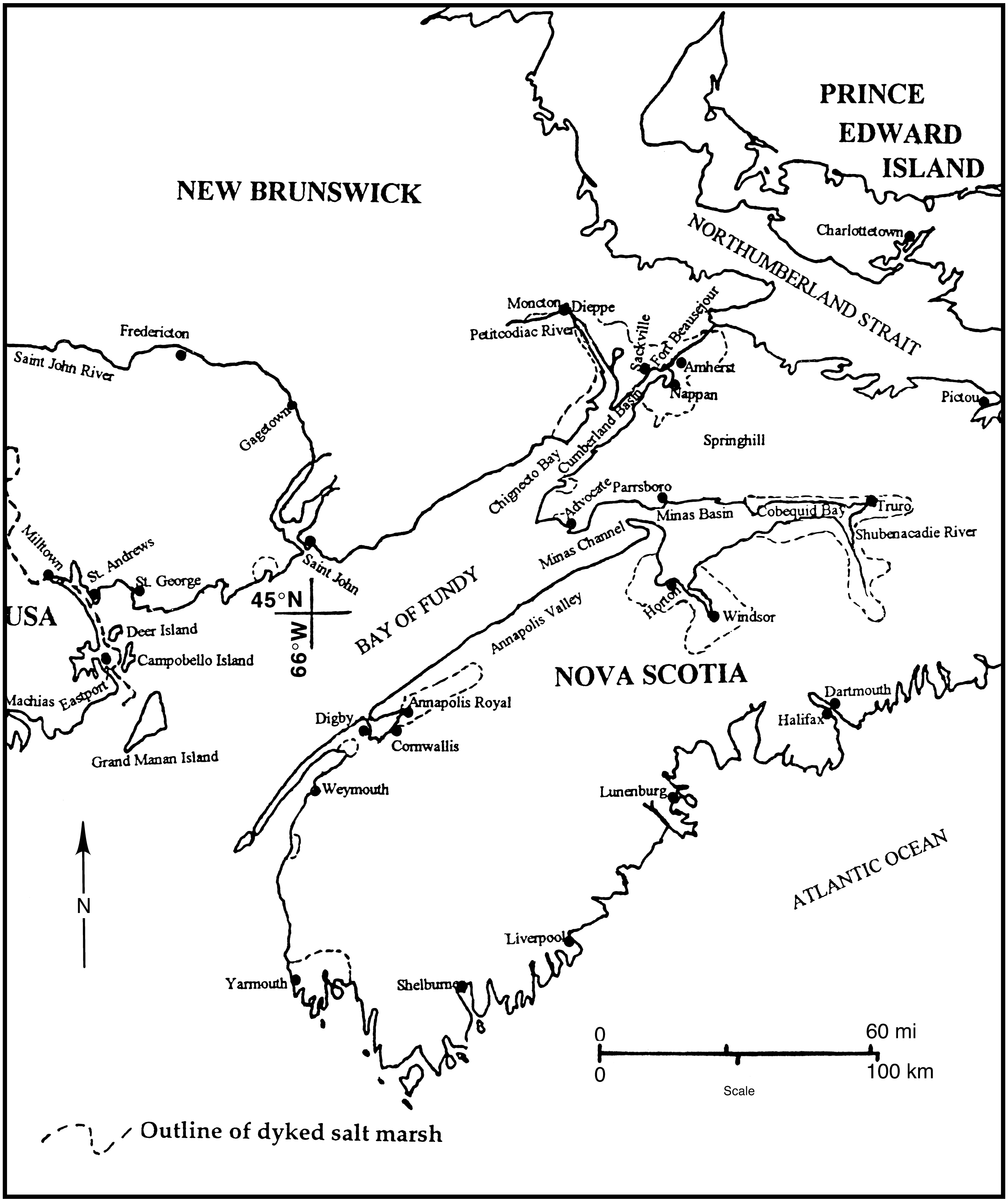


Fig. 60 Map of the Bay of Fundy region showing selected place names in Nova Scotia, New Brunswick and Prince Edward Island and the general location and extent of dyked salt marshes (broken lines). Modified from cartography by MRMS and Milligan (1987).

of the remaining undyked tidal marshes around Cumberland Basin (see below). The number of tides that are able to cover the marsh to a depth of 0.5 m or more is 11 (SD = 5). These peak tides come in sets at monthly intervals, and a group of these sets appear at intervals of 7 months, 4.53 years and 18.03 years. Consequently, for long periods there will be no tidal flooding of the marshes. Thus Fundy tidal marshes can not be viewed as natural hatcheries or nursery areas for saltwater fish (Gordon *et al.* 1985). However when an overflow does occur, silt content of the water tends to be very high. Silt deposition on the marsh depends on the frequency of tidal flooding and the silt content of the tidal water. In the upper reaches of the Bay, the silt content is much greater than near the mouth of the Bay, although the frequency of tidal flooding is much less. Which factor is of greater consequence is open to debate. Sediment deposition upon the marsh causes a rise in elevation of the marsh in the same order as the rate of submergence of the region (Allen 1995).

In summer the soil can dry out, producing mudcracks up to 5 cm wide and 40 cm deep, a geological feature usually taken to signify prolonged aridity. The vegetation on such areas must be able to tolerate occasional flooding with silt-laden salt water, alternating with long dry spells (Gordon *et al.* 1985). Few species of plants are able to do this. *Spartina alterniflora*, a pioneer in this environment, is able to withstand the effects of frequent flooding: however even this species has its limitations, and is able to grow in tidal creeks only to a level one metre below the marsh surface. The lower parts of the creek are bare of plant life. On the flat, high marsh another species, *Spartina patens*, is short and dense, promoting its requisite moist soil conditions over reasonably long intervals of time. Unfortunately neither species of *Spartina* contributes much fertility to the marsh, for they are short of plant nutrients such as calcium and phosphate. Nor is fertility enhanced by the silt-rich tidal marsh soil. These offer far less in terms of ion exchange capacity than, say, the calcium-rich clays of western Europe marshlands, or for that matter, New England marshlands (Desplanque 1952; 1985). As we shall see, intertidal flats of estuaries may vary seasonally, storing clay and silt during the summers and freeing them to winter waters (Amos 1995a, 1995b).

The apparent contradiction that marshes in areas with strong tides are less often covered with sea water than those where tidal amplitudes are low, is explained by reference to Table 19. Here, the height of High Water has been measured from Chart Datum, the average of the lowest predicted annual low water level over an 18.61 year period. Mean Sea Level (MSL) in the Maritimes has been rising relative to the landmass during the past several thousand years. Using all the hourly readings taken from 1927 to 1975, the variable distance between MSL and Chart Datum (CD) at Saint John, N.B., can be expressed as:

$$Z_0 = 13.666 + 0.011834 \cdot (Y - 1927)\ \text{ft} = 4.165 + 0.003607 \cdot (Y - 1927)\ \text{m} \qquad \textbf{(54)}$$

where Z_0 is the vertical distance that M.S.L. is higher than C.D. on 1 January of the year Y.

Using the above relationship, as of 1 January, 1956, the value of Z_0 was 4.270 m or 14.010 ft (MMRA. 1950–1965). In Table 19, this value is used to estimate tidal amplitudes over a ten year interval. These data were used to calculate the S-shaped curve of Fig. 61, which shows the number of tides per year that will reach or exceed certain levels above Mean Water Level. According to the Canadian Tide and Current Tables, Mean Water Level (MWL) is defined as the height above Chart Datum of the mean of all hourly observations used for the tidal analysis at that particular place. At Saint John, N.B., there is most likely a changing difference in elevation between the MWL and the Geodetic Datum; hence MWL is used because it is linked to the local tidal movements.

Figure 61 is an example of what is known as a combination chart or nomograph, a type of chart widely used in engineering (Davis 1943). It does not have a horizontal axis (abscissa), employs a natural scale (rather than logarithmic), and displays the results of calculations which combine various functions (i.e., multiplication or division with addition or subtraction) based on observed tides at Saint John, N.B. The strength of the tides at several other stations in the region are represented in Fig. 61 by lines, the slopes of which are determined by the distance from the reference point (0 km) of Bar Harbor, Maine (see also Desplanque and Mossman 1998b).

From Bar Harbor, Maine, to the head of the Bay of Fundy the range of the dominant semidiurnal tides increases in magnitude exponentially at the rate of about 0.36% per kilometre. This rate is equivalent to 3.66% per 10 km, 43.2% per 100 km, etc. Given this 0.36% exponential increase in tidal range, when the high water level at Bar Harbor is 1 m above MSL, the level 196 km distant at Saint John can be calculated in the same manner as compound interest. The type of calculation is of course based on an exponential growth, and in this instance yields about $1 \times 1.0036^{196} = 2.02$ m. Similarly, the ratio between Bar Harbor water levels and those 366 km distant at Burntcoat Head, N.S., is $1 \times 1.0036^{366} = 3.73$ m.

Most salt marshes in the Bay of Fundy are raised to the level of the average tide, that is the MWL, in the 18-year cycle. Also, the number of high tides per year will vary considerably, depending on the phases of the three main tide-generating astronomical factors. As shown in Table 20, these coinciding peaks run in cycles of 0.53, 4.53 and 18.03 years.

Applied to variations in the levels of Bay of Fundy tides, the High Marsh Curve on Fig. 61 follows places where the local marsh level is assumed to be 1.2 m below the high water level during extreme high tides. It simply shows that the frequency of tidal flooding is much less in the upper reaches of the Bay of Fundy than in cases near its mouth. Drawn from a large data base, the S-curve in Fig. 61 shows the range in number of tides that can exceed a certain level. Taking the marsh level as an example, at Saint John it is approximately 3.5 m above MSL. The intersection with the S-curve shows that at Saint John the marsh will be flooded between 130 to 230 (C-B) times per year, depending upon when it happens during the 18 year cycle. At Bar Harbor, the number of annual floodings is between 660 and 700 (F-G), whereas the Cumberland marshes can expect only about 15 to 60 per year. (D-E).

Table 19. Numbers of times per year that tides in Saint John, New Brunswick, reached to, or above, certain heights above Chart Datum (CD) and Mean Sea Level (MSL) during a 20-year interval (1947-1966)

Height above CD	Height above MSL		Number of events during one year		
ft	ft	m	Minimum	Mean	Maximum
29.5	15.171	4.624	0	0.05	1 (1953)
29.0	14.671	4.472	0	0.15	1 (1953)
28.5	14.171	4.319	0	2.20	7 (1963)
28.0	13.671	4.167	3 (1948)	9.95	20 (1963)
27.5	13.171	4.014	12 (1948)	26.15	38 (1962)
27.0	12.671	3.862	30 (1951)	50.35	77 (1958)
26.5	12.171	3.710	55 (1951)	83.95	114 (1958)
26.0	11.671	3.557	94 (1950)	129.00	167 (1961)
25.5	11.171	3.405	138 (1950)	189.95	236 (1960)
25.0	10.671	3.253	190 (1949)	266.80	323 (1960)
24.5	10.171	3.100	252 (1949)	351.65	430 (1960)
24.0	9.671	2.948	338 (1949)	437.30	503 (1963)
23.5	9.171	2.795	428 (1949)	513.30	582 (1958)
23.0	8.671	2.643	497 (1949)	579.15	644 (1958)
22.5	8.171	2.491	584 (1949)	633.05	679 (1958)
22.0	7.671	2.338	636 (1949)	668.60	697 (1962)
21.5	7.171	2.186	677 (1950)	690.35	704 (1958)
21.0	6.671	2.033	689 (1950)	701.25	705 (1958)
20.5	6.171	1.881	699 (1950)	704.15	706 (1956)
20.0	5.671	1.729	703 (1951)	705.25	708 (1958)
19.5	5.171	1.576	704 (1955)	705.45	708 (1956)

Table 20. Analysis using simple multiples of astronomical cycles governing tides

Perigean	Spring	Declinational	Period
7P = 192.88	13S = 191.95	14D = 191.25 solar days	0.53 years
60P = 1,653.27	112S = 1,653.71	121D = 1,652.96 solar days	4.53 years
239P = 6,585.54	446S = 6,585.32	482D = 6,584.50 solar days	18.03 years

Notes. Calculations show that the peaks of P = perigean cycles (27.554 days), S = spring tides (14.765 days), and declinational cycles (13.661 days) closely coincide at the intervals given. The closest coincidence occurs at an interval of 18.03 years (circa 6,585 days). (After Desplanque and Mossman, 1998a)

Note also that the number of tides/year that will exceed a certain level at a given location is readily determined from Fig. 61. For example, with reference to Mean High Water (line X–W on Fig. 61), a minimum of 254 tides/year, or a mean of 354 tides/year, or a maximum of 433 tides/year (read off the ordinate), will exceed an elevation of 1.55 m (above MSL) at Bar Harbor, 3.10 m at Saint John, and 5.75 at Burntcoat Head (and 7.65 m at Truro). Although the data for Truro are not included, the last number illustrates the point that although the tide level at Truro exceeds that at Burntcoat Head, the tidal range is less at Truro because the floor of the estuary is higher and falls dry during ebb tides. The Shubenacadie River estuary, roughly midway between Truro and Burntcoat Head, illustrates the intermediate case: whereas the tide reaches its highest level about 9 km upstream on the Shubenacadie, MWL occurs at the river's mouth (see Fig. 36, curve 2, and contrast points L and B respectively).

9.7. HISTORICAL DEVELOPMENT OF THE TIDAL MARSHES

In 1632, after about 25 years of exploration, colonization by Europeans of the lands surrounding the Bay of Fundy began in

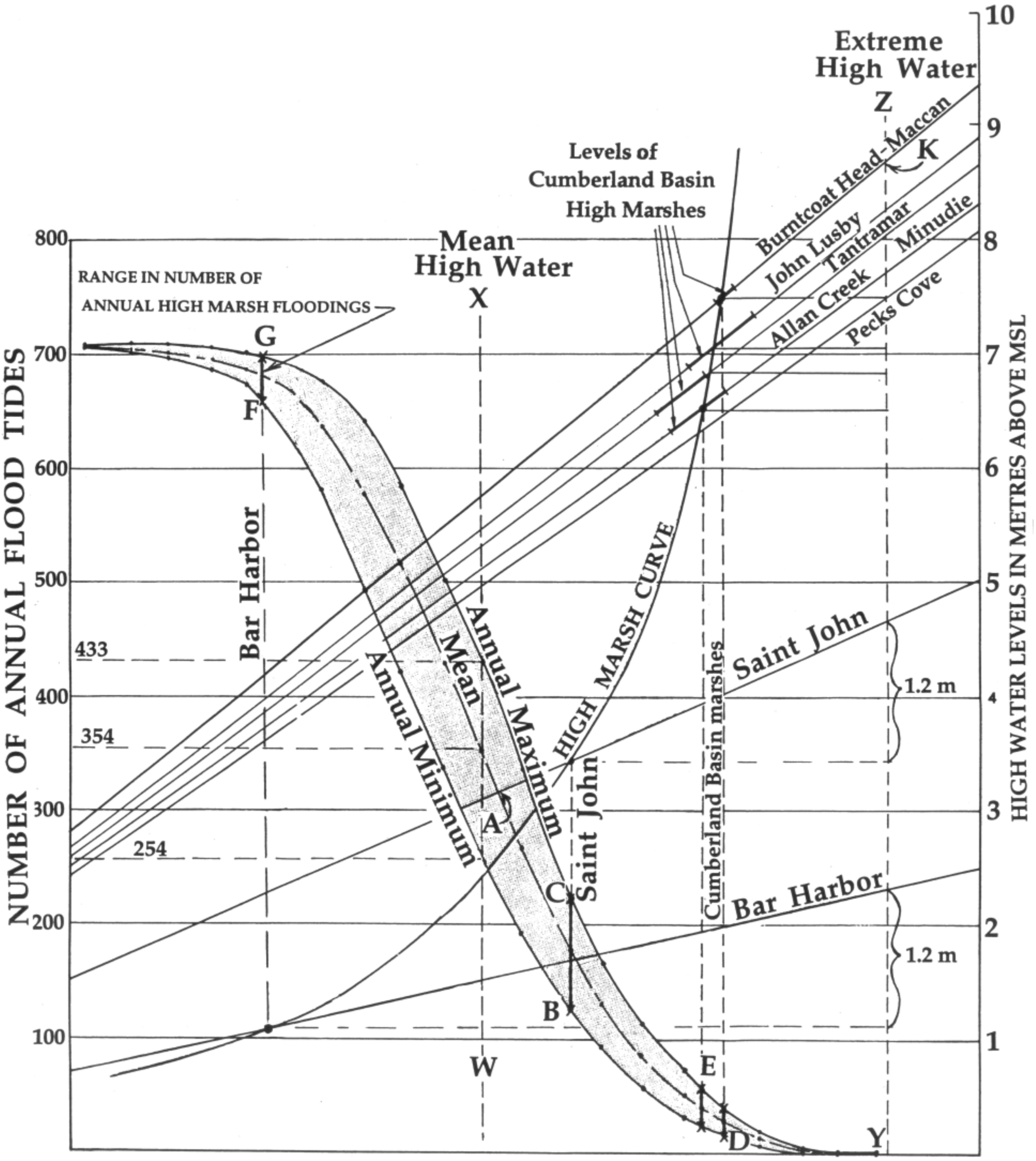


Fig. 61 Combination chart showing the number of tidal floodings (read off the vertical axis) that can exceed a certain level on Bay of Fundy Marshes, based on observed tidal heights at Saint John, N.B. (1947 through 1966). The straight sloping lines from Bar Harbor, Saint John, Pecks Cove and Cumberland Basin high marshes give the corresponding tidal ranges. Mean High Water (**MHW**) and Extreme High Water (given in official Tide Tables for each station) are marked by the intersection of the sloping lines with WX and YZ, respectively. The Extreme High Water Level above Mean Sea Level (MSL) reached, for example at Burntcoat Head-Maccan, and read along YZ at K, is 8.7 m. The MHW level (A) at Saint John is about 3.1 m above MSL. The High Marsh Curve is an empirical auxiliary curve to determine the number of annual floodings of tidal marshes. Local marsh level is assumed to be 1.2 m below the high water level during extreme high tides. Where the High Marsh Curve crosses the sloping lines for the given tidal stations, vertical lines extended to intersect the S-shaped set of curves show the annual number of expected tidal floodings of out-to-sea marshes. Thus, for Bar Harbor, the number of floodings ranges between 660(F) and 700(G); for Saint John, between 130(B) and 230(C); for marshes along Cumberland Basin, the number of floodings ranges from only about 15(D) to 60(E).

earnest. The settlers came from the Loire region of France, attracted by the coastal marshes. They were well acquainted with the techniques of dyking and draining in and around coastal marshes in their homeland as a result of activity by Dutch engineers invited to France in 1599 by King Henry IV. First to be reclaimed under this scheme were the Petit Poitou marsh along the Loire (1599–1642) and the Petit Flandre marsh in the Saintonge district near Rochefort (1607–1639) (Montbarbut 1985; Griffiths 1992). Early Acadian settlers applied the same techniques to tidal marshes in the New World. It was far easier to prepare this land than to clear thickly forested uplands (Fig. 62). At first the process proceeded peacefully. However, the struggle for political hegemony resulted in the forceful removal from the region in 1755 of approximately 10 000 settlers of French descent ("Acadians"). They were replaced by settlers from the British Isles and New England. The French had exploited to the limit the potential for dyking and draining the existing vegetated high salt marsh to form polders (van Veen 1939). Today 36 000 hectares of dykelands form a significant percentage of land suitable for agriculture in the Maritime Provinces of New Brunswick and Nova Scotia.

Elsewhere in the world are similar landscapes: the polder landscape of The Netherlands is often used as the prime example of this cultural environment. There, over 350 000 hectares of land have been reclaimed from the sea and another 1 300 000 hectares are protected against occasional storm tides. In Bangladesh 1 500 000 hectares of land are protected against tidal flooding, although 30–40% of its land area (144 000 km²) is flooded by river water during 4 to 6 months of the year. The technique of protecting such land is everywhere identical, with flood-prone areas protected against high sea levels by dykes. The dyked land is drained by means of gravity sluices or pumps. In the Bay of Fundy area, the tidal range is so high that during much of the day the sea level is much lower than the dyked land, no matter how strong the tide. This means that gravity drainage is possible almost all of the time. For smaller tracts of protected lands, sluices with clapper gates are used, while in larger projects, gates are operated electrically. Clapper gates allow fresh upland water to flow into the sea while blocking seawater from flowing inland over the marsh. Gated drainage sluices within the dyke are called *aboiteaux*. Although there are many versions of this term, the original word may have been *abat-eau* (protector against the water), similar to *abat-vent* (windshield), *abat-jour* (Sun shade) *abat-son* and *abat-voix*

Fig. 62 Illustration shows the Acadians of Minas building of a dyke and an aboiteau near Grand Pré, Nova Scotia. Painting by Lewis Parker, in Dunn (1985, p. 11). Reproduced with permission.

(sound boards). The version *abateau* remains in use in the Saintonge district of France.

Most of the dyked marshes in the Bay of Fundy occur at the head of Cumberland Basin, the central of three main arms of the Bay. Along the Basin, which has a surface area of 118 km², 147 km² of dykelands have been created. The Tantramar marshes east of Sackville, N.B., along the estuaries of the Tantramar and Aulac Rivers, form the largest block at (72 km²), according to Griffiths (1992) "… the largest salt-marsh lands in the world…" (see Fig. 61).

The surface of most of the dyked marshes is 2 m or more below the highest level reached by the tides, while the salt marshes have an average elevation of 1.2 m below that level. Dyke elevation is of course partly attributable to the geologically recent submergence of the landmass relative to sea level in the Maritimes. Another important factor is the length of time that the dykelands have been deprived of additional sediment. For example near Amherst, N.S., dykes protecting the John Lusby marsh were breached during storms in late 1949 and early 1950. The damage was so extensive that no efforts were made to reclaim the land. The following tides built the marsh up a metre or more, burying fence posts in the process, the tops of which are now barely visible above the ground. Another important variable is the rate of erosion. Thus, although tides are higher in the Minas Basin, the coastline along Chignecto Bay is more easily eroded, and this factor may favour the greater abundance of marshes around Cumberland Basin.

The early French settlers, who were mainly subsistence farmers, used the dykelands for a variety of grain, oilseed and fibre crops, shifting later to beef production. The dykelands became the producers of the hay required to feed their livestock during the long winters. Centuries later, when means of transportation were improved and large population centres had developed along the eastern seaboard of North America, the excess hay was exported as fuel for the horse-drawn forms of city transportation. This lucrative enterprise stimulated the urge to increase the acreage of productive land. Most of the sediment carried onto the marsh is deposited in natural levees along the coastline and the tidal creeks leaving the more inland areas with much less sediment cover. As a result, the marsh surface slopes landward towards the edge of the upland where, in saucer-like basins and low-lying areas distant from the coast, freshwater bogs are common. At these sites, bogs with cat-tails and sphagnum vegetation are developed in a zone between the marsh and upland and, in some cases, even in the centre of a marsh. An example of the latter situation is the so-called Sunken Island Bog on the Tantramar marsh near Sackville, N.B. Underlain by marine clays, the bog is a prime example of a floating sphagnum bog surrounded by a fringe of vegetation, characteristic of wet conditions.

It may be no coincidence that after an article on "warping" or "tiding" was published in the British Farmer's Calendar of 1804 promoting the build-up of lands by tidal inundations in Lincolnshire and Yorkshire, a similar project was undertaken in the Tantramar region of New Brunswick. History records that many settlers from Yorkshire came to the Sackville area. Canals were dug between the Tantramar River and several nearby lakes, in the process transforming hundreds of hectares of freshwater peat bog into profitable grasslands.

At the mouth of the Tantramar River, tides have a maximum range of 14.5 m. As an employee of the Maritime Marshland Rehabilitation Administration (MMRA) in July 1952, the senior author made, with the aid of explosives, a 500 m long ditch from the Tantramar River to Long Lake, 22.5 km from the mouth of the river. Within about three years most of this 7.5 hectare lake was completely filled with silt for new farmland, and no longer appears on Topographical maps. The sets of very high tides in 1953 and 1954 contributed greatly to this last "tiding" carried out in the Bay of Fundy area.

9.8. REHABILITATION AND RECLAMATION

Through vigorous efforts, the early French settlers proved the feasibility of dykeland development and utilization. Many remnants of old Acadian dykes exist on sections of marsh that have since been allowed to revert back to salt marsh. It appears that these settlers built their dykes at the very edge of the salt marsh, leaving only a very narrow safety margin for waves to dissipate most of their energy during High Water (Baird 1954). In addition to earth, the settlers also used pole and plank facing. This same method had been used centuries ago in Europe to protect the face of dykes, but was abandoned after shipworm (*Teredo navalis*) invaded the waters of northwestern Europe in the first half of the 18th Century. The teredo consumed all the wooden parts of dykes and sluices and generally promoted wholesale rotting of poles and planking. Weaknesses thus created became foci for wave action, which continued the degradation until eventually holes developed in the dykes; the process is similar to that which results in sea caves and blow holes. Fortunately, teredo is not found in the Bay of Fundy, although it is present elsewhere along the North American coastline. Only a limited number of mollusc species are able to thrive in the upper region of the Bay of Fundy, the common periwinkle (*Littorina litorea L.*) being a recent newcomer. The fact that plank facing is still used in Fundy dykes attracted the German geographer Carl Schott to the area in 1952 to study the application of this ancient form of dyke protection. His work (Schott 1955) remains the best comprehensive report on the Bay of Fundy marshes.

After World War II economic studies indicated that rehabilitation of deteriorated dykes and aboiteaux would be beneficial. Accordingly, the Federal Government financed and carried out the building or rehabilitation of 400 km of dykes and new sluices, while provincial governments and landowners agreed to share the cost of associated drainage facilities. Several former dykelands were in such a state that no rehabilitation was attempted. Of these lands, a few have been acquired by the Canadian Wildlife Service to serve as National Wildlife areas, some of which are important stopover and feeding areas for migrating waterfowl. Low-lying sections of the dykelands, especially those fringing the uplands, were dyked off internally and transformed into waterfowl habitat (work that is financed and carried out by that uniquely North American organization, "Ducks Unlimited"). Some tracts of dykeland are small parcels of land sandwiched between the upland and meandering tidal estuaries. The required height of the dykes is only about 1.5 to 2.0 m above the original marsh level.

Present-day dyke construction is carried out using bulldozers and draglines. Topsoil is first removed from the projected dyke site and stockpiled for later re-installation. The bulk of the dyke material is taken from the drainage ditch running inside and parallel to the dyke. Any necessary additional material is taken from borrow pits outside the dyke. The outside face on exposed sections of dyke is covered with quarried rock trucked in during the winter when the dykes are able to withstand heavy traffic. These rocks dissipate wave energy generated during High Water.

The dimensions of the aboiteaux or discharge sluices are determined by a number of equations that take into account potential storm runoff from the watershed to be discharged through the sluice, the ranges of the local tides, the elevation of the dykeland, and the sluice invert elevation allowed by the receiving tidal channel. For sluices built in larger creeks and estuaries the available storage volume of basins upstream of the sluices is taken into account, as well as the probable hydrographs of the storm runoffs.

The large tidal ranges in the Bay of Fundy permit exclusive use of gravity drainage. Pumped drainage is uneconomical and would only be required for short periods during High Water should tide water exceed the water levels upstream of the sluice, and only then if the storage volume was insufficient to hold the watershed runoff during that period. Such occasions would be so rare that the large capacity pumps would hardly ever be used.

Some 435 small aboiteaux were built by the Maritime Marshland Rehabilitation Administration in the 1950s and 1960s. Dimensions ranged from 0.3 × 0.3 m boxes to multiples of 1.2 × 1.5 m boxes, set side by side and made from chemically treated lumber. More recently, sluices have been built with asphalt-coated corrugated steel pipe. The flapgates are made of bronze or steel and hung by horizontal hinges or steel chains. The latter method appears superior for it allows debris to pass through the sluices with less damage to the gates.

To eliminate the need to rehabilitate tens of kilometres of dykes and numerous small aboiteaux, six large tidal sluices were built in larger tidal estuaries (those of the Annapolis, Avon, Memramcook, Petitcodiac, Shepody and Tantramar rivers). The largest of these structures are the five 8.8 × 8.8 m sluices (with inverts at 1.5 m below MSL) set in the Petitcodiac River estuary near Moncton, N.B. Two slightly smaller sluices in the Annapolis River estuary were converted in 1982 into an experimental tidal power station (see section 7.5). The large tidal sluices are steel-reinforced concrete structures with flared entrances and are equipped with electrically hoisted gates which can, if necessary, be operated manually. These gates can also be electrically heated for use during periods of heavy frost. In the larger estuaries the sluices were not able to pass enough water during the time of dam construction. Therefore auxiliary sluices were built to keep tidal currents in the closure gap at manageable speeds. Later on these sluices were buried within the dam itself. These dams also serve as causeways for highway and rail traffic, shortening the connecting links among the provinces to a significant degree.

The operation and management of dykelands are carried out under the direction of "marsh bodies", elected by landowners and assisted by officers from the provincial departments of agriculture. There are 86 such "marsh bodies" in Nova Scotia and 39 in New Brunswick.

The reclamation of Fundy tidal marshes has been regarded by some people as ecologically disastrous in light of recently publicized figures of salt marsh production. For example, in semi-tropical Georgia, *Spartina alterniflora* has been measured at 2883 gm^{-2}/yr, a figure greatly exceeding that of other forms of natural vegetation or agriculture (see Pomeroy and Weigert 1981). In Virginia, the measured rate of production is 1143 grams, in Rhode Island 668 grams, and on high marshes around Cumberland Basin a mere 400 gm^{-2}/yr. Factors responsible for the relatively low production of salt marsh vegetation in Cumberland Basin include: the shortness of the growing season, nutrient limitation, inundation characteristics, sediment aeration and, last but not least, tidal stress.

Unfortunately, the Georgia figures are most often used in ecological arguments naming the Bay of Fundy a disaster area. Simply put, Fundy tidal marshes can remain dry for months on end and thus cannot be construed as hatcheries or nursery areas for saltwater fish. The dyking of the high marsh in the upper reaches of the Bay will not have had the same biological impact as results from utilization of marshes in more southern latitudes, or in regions with smaller tides. Nor is there much basis for stating that reclamation of the salt marshes has been detrimental to the region's bird population. When the French settlers arrived in the upper reaches of the Bay, they called the area "Tintamarre" because of the birdcalls that filled the air. The present name of the Tantramar marshes derives from this word, which means din, racket, or noise. With this explanation comes the idea that the original undyked salt marshes had a rich birdlife. It is interesting to examine this proposition.

In The Netherlands, until recently, every hectare of reclaimed or unreclaimed marshland seemed to have its own resident couple of lapwings, godwits, and skylarks, and every acre of water its pair of mallards. This was the case despite the dense human population and intense agricultural use of the polderland. More intense agricultural practices and use of pesticides have recently changed this picture drastically. In contrast, Maritime marshes are almost devoid of birdlife, especially the out-to-sea marshlands. The French may possibly have named the marshes "Tintamarre" during the spring migration period when the marshes are staging areas for geese and ducks, or during the late summer period when hundreds of thousands of waders congregate at selected areas.

Overall, the Fundy marshes have very little bird life. Indeed, the salt marshes could never have provided suitable nesting habitats for birds because there is a total lack of trees.

Furthermore, the infrequent monthly flooding of the marsh with salt water, which occurs in sets that arrive about 47 days later from year to year, makes the marshes unsuited for ground breeders. Since these floodings are more intense every 4 to 5 years, it seems improbable that bird species could have become used to monthly floods and incorporated them into their genetic programs. This leaves only breeding areas for birds like the raucous redwing blackbirds that can multiply among the cat-tails in transition areas between the salt and freshwater marshes. This may well have been the "tintamarre" that so impressed the French settlers.

The dyking of marshes has had another, less remarked upon effect (Teal and Teal 1969). Before dyke construction, tidal marshes acted as sinks for excess suspended sediment in the system. Following dyke construction, this suspended material may have resulted in changes to the habitats not only of plankton, but also of fish like shad and gaspereaux. Historical records show that in 1837, vessels from 50 to 150 tons were able to sail almost daily up Cobequid Bay and the Salmon River to receive and discharge cargo near the now defunct Board Landing Bridge near Truro (see Fig. 60). After 1867, however, siltation of the river prevented further shipping access. Similarly in England by about 1888 all the harbours on the southeast coast of England were silted up due to dyking of marshes, requiring a vast expenditure for constant dredging to keep harbours operational.

Very little use is being made of salt marshes for socio-economic purposes unless the terrain is transformed to dykeland. Dykelands provide pasture, especially for sheep, and a source of "wild" hay. Some plants such as *Salicornia* and *Plantago* were eaten as a vegetable on a minor scale (Trueman 1896). The marsh is generally inaccessible and unattractive to conventional recreation seekers. Fundy salt marshes are cold in winter, wet in the spring, mosquito ridden and covered with nearly impassable vegetation during the summer and early fall, and muddy throughout the year. In fact, smells emanating from marshes are usually so obnoxious that they have a serious effect on the recreational usefulness of adjoining shore properties. The only "recreational use" of salt marshes is the realization of their importance within ecosystems.

Today, although an estimated 90% of the original salt marshes at the head of the Bay of Fundy has been reclaimed by dyking, much of the rest remains idle. The once lucrative hay market has disappeared. Few if any people actually live in the tidal marsh area itself. Farmers use the land around their farmsteads with the most effect and the greatest care. However the further the land is removed from their daily supervision the less attention it receives. An enduring myth is that marshlands are very fertile, whereas in fact they are limited in some plant nutrients such as calcium and phosphate. The silty soils also offer far less in terms of ion exchange capacity than, for example, the calcium-rich clays of west European marshlands. One can argue whether the present-day utilization of the Bay of Fundy dykelands is what it should be, but it appears that the benefits derived from them over the centuries far outweigh any disadvantages caused by dyking the high marsh areas.

10. Storm Tides in the Bay of Fundy

10.1. INTRODUCTION

Storm tides (here taken as synonymous with storm surges) generally spell trouble. A positive storm tide is a large rise in water level accompanying a coastal storm, the water rise caused by violent winds and low atmospheric pressure. Conversely, with high atmospheric pressure, a negative storm tide may lower sea level from its predicted value (Wells 1986; Parkes *et al.* 1997). When a storm tide coincides with an exceptionally high astronomical tide and shallow water depths, the results may be little short of catastrophic. The record of storm tides is knowable, and they may be predictable in the Gulf of Maine-Bay of Fundy region. Inevitably they are linked to pressure changes in the atmosphere, and to wind set-up.

10.2. ATMOSPHERIC PRESSURE CHANGES AND WIND SET-UP

Atmospheric pressures deviating from the normal can cause appreciable changes in sea level. Where pressure is high, sea level will drop, while the excess water moves to the areas where the pressure is below normal. A difference of one kiloPascal (1 kPa = 10 millibars) can effect a 0.0975 m change in sea level. Such differences are more easily detected in areas of very small tides, an example being the Bras d'Or Lakes on Cape Breton Island, N.S., which are connected to the ocean by small channels restricting the daily tidal movements of water. In part, the salinity levels in these lakes are maintained because of changes in water level caused by variable barometric pressures responding to cycles longer than the semidiurnal and diurnal tide cycles.

In Maritime Canada as a rule the largest deviations from normal of atmospheric pressure occur during fall and winter (see Table 21). A possible deviation from the mean of 5 kPa means that sea level at times can be raised nearly 0.5 m. This is not so great as to create flood conditions, unless coincident with the High Water of extremely high tides. Unfortunately, statistics on air pressures are not readily available. However the Monthly Meteorological Summaries of the Truro station in Nova Scotia indicate that a deviation of 2 kPa or more occurs during three or four months of each year, and that a deviation of 4 kPa may occur more than once a year.

Sea level also may be raised above normal due to a wind/storm "set-up" (see Fig. 63). This is a flow of air that drives the water toward the shore line. Here the gradient of the water is balanced by the shear stress of the wind blowing over the water. Quite apart from the set-up which propagates into the Bay due to wind over the Gulf of Maine and Scotian Shelf, in the upper reaches of the Bay of Fundy the tides (here, in reference to total water level; i.e., tide plus storm surge) are large and at times the currents are very strong. Currents in the Minas Channel can run at the rate of 7 to 8 knots (3.5 to 4 ms^{-1}), while in the Minas Basin and Chignecto Bay the rates drop to 2.5 to 3 knots, increasing again in Cobequid Bay and Cumberland Basin to over 4 knots. Winds blowing against the current will, in effect, lessen the height of the tide and the rate of the current, but they may create tidal rips in which the surface waves are steepened to the point of breaking, causing violent seas.

The wind set-up is estimated by an equation which takes

Table 21. Mean and least atmospheric pressures measured at Truro, Nova Scotia, and at Moncton, New Brunswick (pressure in kiloPascals)

	Truro				Moncton			
Month	Years of observ.	Mean	-Low	=Diff	Years of observ.	Mean	-Low	=Diff
January	16	100.76	96.39	4.37	38	100.32	95.51	4.81
February	16	100.64	96.66	3.98	37	100.18	95.68	4.50
March	16	100.67	95.39	5.48	37	100.24	95.54	4.70
April	16	100.80	96.80	4.00	37	100.37	96.48	3.89
May	16	101.10	98.20	2.80	37	100.46	97.61	2.85
June	16	100.90	98.60	2.30	37	100.35	97.64	2.71
July	16	101.00	98.90	2.10	37	100.42	98.42	2.00
August	16	101.00	98.60	2.40	37	100.44	97.80	2.64
September	16	101.20	98.40	2.80	37	100.73	96.41	4.32
October	16	100.90	96.90	4.10	37	100.63	96.38	4.25
November	16	100.90	96.90	4.00	37	100.52	96.14	4.38
December	15	100.74	96.03	4.71	37	100.36	94.69	5.67

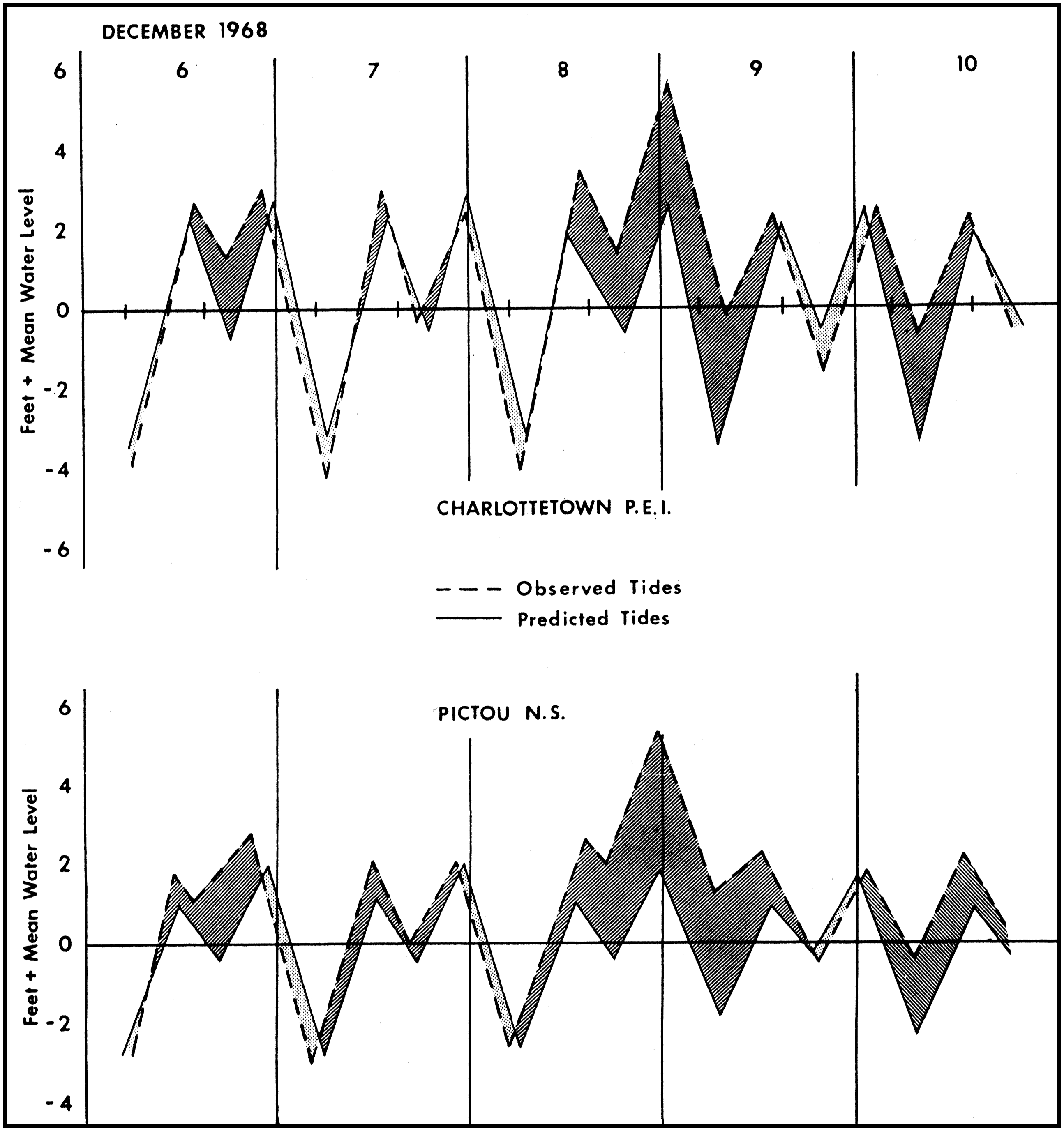


Fig. 63 **Storm set-ups at Charlottetown, Prince Edward Island, and at Pictou, N.S., 8 December, 1968, clearly illustrate the markedly different levels in observed tides compared to levels predicted on the basis of astronomical relations between Sun, Moon and Earth. At both localities, observed tides have a greater range than predicted tides during the surveyed 5 day interval of storm set-up.**

into account wind speed, fetch, angle between wind direction and direction for which the set-up is calculated, and the depth of the section of water. For each section with a different depth a separate calculation is made. After passing over all sections, the total wind effect will depend upon the fetch (distance over water that the wind is active). The following equation can be used to estimate the wind set-up (S_x) along the shoreline:

$$S_x = (3.09 \pm 0.4)\cdot 10^{-5}\cdot U^2\cdot \cos(A)\cdot X/D \qquad (55)$$

Where Sx = wind set up in m, over the fetch section; K=stress coefficient [Lorentz used $(3.09 \pm 0.4)\cdot 10^{-5}$; U.S. Corps of Engineers uses $2.36\cdot 10^{-5}$]; U = wind speed in km/hr; A = angle between wind and fetch direction; X = length in km, of fetch section with depth (D) in metres.

Fig. 64 An old postcard image of Beacon Lighthouse at Sand Point, N.B. (now the terminus of the Canadian Pacific Railway at Saint John Harbour), which replaced the first Beacon light, which was destroyed by fire two years before the Saxby Tide. Beacon Lighthouse was declared surplus, and destroyed in 1913.

When the set-up becomes 10% of the depth, which happens when the wind speed exceeds approximately 60 times the depth in m, (**55**) results in too large values of S_x. It is better replaced by:

$$S_x = [(2 \cdot k \cdot U^2 \cdot \cos(A) \cdot X/D^2 + 1)^{0.5} - 1] \cdot D \qquad \textbf{(56)}$$

Note that the set-up is smaller when the depth is larger. One would thus expect that during High Water the wind set-up would be less than with Low Water. However in tidal waters where the large sections fall dry during Low Water the increased fetch during High Water can more than offset the influence of increased depth.

In areas where the tidal range is small, storm conditions can raise water levels somewhat above that of ordinary tides. In the upper reaches of the Bay of Fundy the difference between levels reached during large tides and small tides may exceed 4 m, and wind set-ups occurring during larger tides may cause flood conditions. Severe flood conditions are virtually guaranteed when adverse weather conditions coincide with the High Water of extremely large, astronomically-caused tides. The probability of such a coincidence is small and very difficult to estimate. However, indications are that in the Maritime Provinces of eastern Canada such conditions have occurred at intervals of more than a century. Historical accounts document two occasions when great storms coincided with a very high tide. These occasions were October, 1869, and November, 1759.

10.3. THE SAXBY TIDE, 1869, A PREDICTION FULFILLED

On the afternoon of 4 October, 1869, Thomas Earle tried to leave Beacon Light at Sand Point in Saint John Harbour (Fig. 64), but heavy seas drove him back. As wind and waves continued to rise, water flooded the first floor of the lighthouse, and threatened to rise higher. Waves broke over the top of the lighthouse, carrying away the bell and smashing the windows and the globe protecting the gas light. Retreating to the middle story, the keeper closed the hatchway behind him. The gas light continued to burn, and fanned by the storm, ignited the superstructure. In desperation Earle managed to fit a spare globe around the light, and was somehow able to contain the fire. Three and a half hours later the tide receded sufficiently to allow him to gain the safety of higher ground.

Thomas Earle, like most coastal folk along the Bay of Fundy, was used to high tides. He would have known the difference between "spring" and "neap" tides. He knew too that storms can cause unusually high water levels, especially when coincident with an otherwise normal high tide. Normally he would have relied on the Farmers' Almanac to predict tidal conditions throughout the year. But conditions in the Bay of Fundy on 4–5 October, 1869 were not normal.

Earle may never have heard of Pliny the Elder, or of Sir Thomas Herschel, who in 1860 helped sustain the legend of 120 foot-high tides by repeating the myth of the 4th Century BCE navigator, Pytheas. However he probably had read in

Maritime newspapers about S.M. Saxby's dire prediction of the great storm from which he was to only narrowly escape. The prediction had been published the previous November in the British newspapers *London Standard* and *London Press* (Saxby 1868). It read:

> "I now beg to state with regard to 1869 at 7:00 a.m., October 5, the Moon will be at the part of her orbit which is nearest the Earth. Her attraction, will be therefore at its maximum force. At noon of the same day the Moon will be on the Earth's equator, a circumstance which never occurs without marked atmospheric disturbance, and at 2 p.m. of the same day lines drawn from the Earth's centre would cut the Sun and Moon in the same arc of right ascension (the Moon's attraction and the Sun's attraction will therefore be acting in the same direction); in other words, the New Moon will be on the Earth's equator when in perigee, and nothing more threatening can, I say, occur without miracle. With your permission, I will, during September next (1869) for the safety of mariners, briefly remind your readers of this warning. In the meantime, there will be time for repair of unsafe sea walls, and for the circulation of this notice throughout the world."

Saxby, a civilian instructor of Naval Engineers of the British Royal Navy, published books and almanacs of weather predictions, claiming a relationship between stormy weather and the Moon crossing through the plane of the Earth's equator. As this occurs every two weeks it could be said that Saxby gave himself a better than 50 percent chance of claiming reliable forecasts. Note that Saxby did not specify the location where his threatening tide would occur. Astronomic conditions were to be right for higher than normal tides, world-wide, on 5 October, 1869.

The prediction was fulfilled in the Bay of Fundy by what was to become known as the "Saxby Tide" or "Saxby Gale". A storm hit the North American eastern seaboard on 4 October, 1869. All along the New England coast severe flooding and wind damage occurred. Between Washington and the upper reaches of the Bay of Fundy, more than 150 vessels sank or were blown ashore, 121 of them between St. Andrews, N.B., and Machias, Maine. Near Point Lepreau, N.B., the barque *Genii* was wrecked and eleven lives lost (Ganong 1911; Tibbets 1967).

At 17:00 hours, the wind increased to a gale, and an hour later rain began. By the evening of 4 October, Saint John streets were littered with debris torn from buildings. The gale continued from the south, reaching hurricane force about 21:00 hours by which time the rain had stopped. Around 22:00 hours the wind shifted to the southwest and subsided. Fully an hour and a half before the tide ordinarily would have reached its peak, waves from the Bay of Fundy were breaking over every wharf in Saint John Harbour. Ships parted from their moorings; some were driven ashore, others were badly damaged. Dozens of wharves, fish shacks, and abutments were washed away (MacLean 1979).

About 160 km northeast, at the head of the Bay of Fundy, the Saxby Tide occurred at 01:00 hours, 5 October, overtopping the dykes by at least 0.9 m. In Cumberland Basin, two fishing schooners were lifted over the dykes of the Tantramar marshes and deposited five kilometres from the shoreline. At Moncton, N.B., the water rose nearly 2 m above the next highest tide on record. On the marshes west of Amherst, N.S., a barn in which some people had been sleeping, was despatched well over a kilometre up the marsh. During the course of the storm two men were carried out to sea and drowned. Three others were able to cling to timbers and were eventually washed ashore. Much of the hay stored on the marsh was swept out to sea and the remainder was scattered over the area. Farmers drew lots in order to divide the little hay that was salvaged. In and around the Minas Basin, the gale was less severe, although the rainfall was heavy. Everywhere dykes were breached, cattle and sheep were drowned, lengthy portions of railroad beds were washed away, and in many areas travel became impossible. Communications likewise were shut down by the weather to a degree difficult to imagine today.

10.4. HEIGHT OF THE SAXBY TIDE

A year after the disaster, a survey was made between 13 August and 31 December for a proposed canal across the Chignecto Isthmus from the Bay of Fundy to the Northumberland Strait. To simplify calculations, by avoiding negative values, the surveyors assumed a datum (reference elevation) of 100 feet (30.48 m) below the average top elevation of the dykes. By this reckoning the Saxby Tide was reported to have reached levels of 100 feet or more. These figures of course have no direct relationship to mean sea level. But they have, unfortunately, helped perpetuate the erroneous notion of enormous tides.

During the 1870 survey, extremely high astronomical tides (i.e. tides not associated with storms) occurred on 23 September (28.83 m), 26 October (28.83 m), and 23 November (28.80 m) for an average of 28.82 m. Comparing this elevation with the average top elevation of the dykes yields (30.48 m–28.82 m) a difference of 1.79 m. Thus although the level of the dykes may have been raised slightly in the years since 1870, the Saxby Tide was at least 1.5 m higher than astronomically caused high tides.

10.5. THE STORM TIDE OF 1759

Only sparse accounts survive of a probable precedent, over 100 years earlier, of the Saxby Tide. The nameless historical storm tide battered the Bay of Fundy region on 3 and 4 November, 1759. In Beamish Murdock's "History of Nova Scotia" contained in the *Gentleman's Magazine* of 1760, it is recorded that at Fort Cumberland (earlier and later named Fort Beausejour) 700 chords of firewood were swept away from a woodyard that was at least 3 m above the protecting dyke. In Saint John Harbour water reportedly rose 1.8 m higher than was usual for large tides. Storm waves broke on the terraces of

Fig. 65 In the aftermath of the Groundhog Day storm of 2 February, 1976, the streets and waterfront of Saint John, N.B., were in a shambles. *Photograph courtesy of Saint John Telegraph Journal.*

Fort Frederick, located well inside the Harbour, demolishing a store house and spilling provisions into the sea.

It is unknown whether anyone foretold the historical storm tide of November 1759. The regionality of storms and storm tides makes predictions like Saxby's a rather unscientific exercise, however much they may impress the local populace. Even today, meteorologists, assisted by a world-wide computerized network of data-gathering instruments on the ground and in satellites, are faced with more variables than they are able to handle (Wells 1986). The behaviour and frequency of complex extraordinary weather systems, their whereabouts, strength, rate and direction of movement, are beyond their grasp.

10.6. THE GROUNDHOG DAY STORM, 1976

Whereas the Saxby Gale was predicted a year before it happened, the "Groundhog Day" storm of 2 February, 1976, was forecast only hours before it broke. Two days earlier a weak low pressure area hovered over Alabama and Texas. Subsequently, this system met a small high pressure system from western Ontario. Small craft warnings were issued on 1 February, advising of strong southerly winds. Then around noon that day, gale force winds were predicted. During the night, gale warnings were changed into severe storm warnings. By 8:00 hours on 2 February, the barometric pressure had dropped precipitously over the Gulf of Maine, signalling the likelihood of a storm accompanied by higher than normal tides (Amirault and Gates 1976).

The storm hit the coast of Maine hard (Morrill *et al.* 1979). In places, the tide rose more than 2.5 m above the predicted level, heavily eroding the coastline. Waves hammered coastal installations. A freighter anchored in Penobscot Bay was blown aground. The strong south-southeasterly winds, which had been blowing for 5 to 6 hours over the open water along the major axis of the Penobscot Bay, resulted in a storm surge in the Bay and up the Penobscot River. Much of Bangor was flooded. In less than 15 minutes the water reached its maximum depth of 3.7 m in the river, 3.2 m above the predicted tide level.

By the afternoon of Groundhog Day (2 February, 1976), the storm was raging along the eastern seaboard (Fig. 65). Intermittent power failures and curious sparking effects were the result of short circuits caused as winds swept seawater across the countryside. Fortunately, the tide was an apogean spring tide (Conkling 1995). In Saint John, the high tide was expected to be only 7.7 m (25.2 ft) above CD at 13:10 hours. Note that for comparative purposes, this is almost exactly equal to mean Higher High Water (25.3 ft) at Saint John. However, on the afternoon of Groundhog Day the tide rose to 9.16 m (29.65 ft) above CD, fully 1.46 m higher than expected. The damage would have been simply enormous had the storm occurred on the perigean spring tides: sixteen days later on 18 February, the tide at Saint John was predicted to reach a height of 8.4 m above CD; a month and a half later, on 18 March, the tide was predicted to rise 8.66 m above CD; two and a half months later on 16 April, the tide was predicted to be 8.84 m above CD, 1.07 m higher than the predicted tide on Groundhog Day. In short, a storm on 16 April, 1976, would have had the potential of causing calamity on the scale of the Saxby Tide.

In light of the above considerations it seems a distinct possibility that another storm tide of the magnitude of the Saxby Tide of 1869 will occur in the Bay of Fundy region. The big question is when will this storm likely occur? Until then, successor dykes to those erected during the 17th Century along the Bay of Fundy marshlands, continue to protect agricultural lands. These agricultural lands are shrinking before the onslaught of modern highway and suburban development schemes, not to mention the continued transgression of the sea. Aboiteaux draining these lands are of course unable to discharge when the tide outside is higher than the water upstream. With a heavy runoff, the potential therefore exists for the land to be flooded with fresh water. This is realized and tolerated by farmers of course, but the situation is rather less stoically accepted by developers.

Generally, the stronger tides happen during spring and summer around midnight, and during fall and winter near noon. But the fact that the Saxby Tide occurred during the night and in the fall shows that even this rule is not valid for extraordinarily severe storm tides. Nor does the fact that the landmass of the upper Bay of Fundy area is submerging at a rate of about 3 mm per year improve the situation. The dykes can be made higher, but if they are not raised to Saxby-type levels, their overflow will raise the flood levels in the dyked areas that much higher. The developed areas near Truro, Weymouth and Advocate in Nova Scotia, and Moncton in New Brunswick (see Fig. 60), are among potential victims of such storm tide events.

11. Periodicity of the Tides

11.1. INTRODUCTION: THE *SAROS* CYCLE

Pytheas, a navigator from the Greek colony of Massalia (modern Marseilles, France), explored the northern Atlantic Ocean in the Fourth Century B.C.E. Proceeding north after passing between the Pillars of Hercules, he noticed the lengthening of the summer days and observed the midnight Sun in Thule, a six day voyage north of Britain. He was aware too, of the relationship between tides and the Moon's motion along its orbit.

Pliny the Elder (23–70 A.D.) mentioned in his *Historia Naturalis* that, according to Pytheas, the tides north of Britain rise to heights of 120 feet ("*octogenis cubitis*"). The notion of the existence of such enormous tides persists. For example, the eminent 19th Century scientists Sir John Herschel and Sir Oliver Lodge repeated the belief that 120 foot-high tides occur in the Bay of Fundy. Only a few years ago the same misconception was linked to the extraordinarily high tides associated with the so-called "Saxby Gale".

One might wonder where the extraordinary high tides occurred that so impressed Pytheas. He must have been familiar with the 40 foot-high (12.19 m) tides that regularly occur along the Brittany coast on the French side of the English Channel, or in the Bristol Channel south of Wales. According to the Roman writer Festus Avienus, these waters were visited a century before by Himilco, a famous Phoenician explorer, and by merchantmen trading for tin. The only other tides in the North Atlantic of the same order of magnitude are the 30 ft (9.14 m) tides in the White Sea portion of the Arctic Ocean, and the more than 40 ft (12.19 m) tides in Ungava Bay, Quebec and the Bay of Fundy. The White Sea can only be reached by waters lying north of the Arctic circle where the midnight Sun can be observed in midsummer. Could Phoenician seafarers have reached the western side of the Atlantic and, after visiting the Bay of Fundy, passed to Pytheas the notion of 120 foot-high tides?

As we have seen, tides are caused by the attraction of the Moon and Sun on water particles near the surface of the Earth. Since the orbits of the Moon around the Earth, and of the Earth around the Sun, are elliptical, the effects are variable in strength, like the resulting tides. The redeeming feature is that every aspect of each motion has a corresponding periodicity to which tidal variations can be related. The pages-long equation describing the paths of celestial bodies, a masterpiece of human ingenuity, was first set out by Louis Lagrange (1736–1813) and Pierre Simon de Laplace (1749–1827). Yet even the ancients possessed considerable knowledge concerning these matters.

Nearly four centuries before Pytheas described the influence that the Moon's motions have on the tides, Chaldean priests in the Middle East were able to predict recurrence of eclipses. This was because of their knowledge of the *Saros*, a Babylonian name adopted by modern astronomers for a cycle with a period of 18 years, 11 days and 8 hours. In this 18.03-year cycle, the Moon, Sun, and Earth return to almost identical relative positions to each other. This is the cycle in which similar solar and lunar eclipses repeat themselves. Eclipses result when the Sun, Moon, and Earth are in, or almost in, one straight line.

The paths of the solar eclipses over the Earth's surface are almost identical in shape, but are located 110° to 130° west of the path of the eclipse of 18 years previous (Abell *et al.* 1988). For example, one series of solar eclipses began on 17 May, 1501 (Julian calendar), as a partial eclipse. (At present, 12 such series producing total solar eclipses occur during a *Saros* cycle of 18.03 years). After 15 *Saros* cycles with partial and annular eclipses, the eclipse became total on 6 November, 1771. The total eclipse seen on 7 March, 1970, over Mexico, the USA and Canada was one of the series; likewise that of 18 March, 1988 as seen over the Pacific, Sumatra and Borneo (see Fig. 66). After this, there will be 35 more total eclipses followed by half a dozen partial ones. All told, the *Saros* prediction is valid for 1226 years $[(1988-1501)+(35+6)\cdot 18.03=1226.23 \text{ years})]$ for this particular series.

Because the astronomical conditions conducive to generating large tides match the *Saros* cycle, their recurrence at 18.03 year intervals is expected. Could it be that this particular timing is closely linked to the occurrence of exceptionally high tides like the Saxby Tide? There is good suggestive evidence that this is the case, but first we need to look further into the causes of tides and their variations. Only then will we better appreciate the implications of the *Saros* for a future tide comparable to the Saxby.

11.2. ASTRONOMY AND THE VARIATIONS OF TIDES

Orbital forcing of tidal cycles is only a small portion of the spectrum (Fig. 67) of astronomically-driven periods which exert gravitational effects on Earth and the affairs of humankind (Rampino *et al.* 1987). The same periodic behaviour governs changes over time in the energy distribution reaching Earth's atmosphere, and must have done so throughout geologic time. We are concerned here only with tidal phenomena within a small portion of the calendar and solar frequency bands.

S.M.Saxby might have added to his prediction that the great storm tide destined to immortalize him, especially in the view of many Maritimers, would coincide with the *Saros* (Desplanque 1974). In this 18.03 year cycle, Moon, Sun and Earth return to almost identical relative positions. It is astounding to realize that by 800 B.C., Chaldean priests knew the *Saros* well enough to accurately predict eclipses. Could it be that eclipses, or more

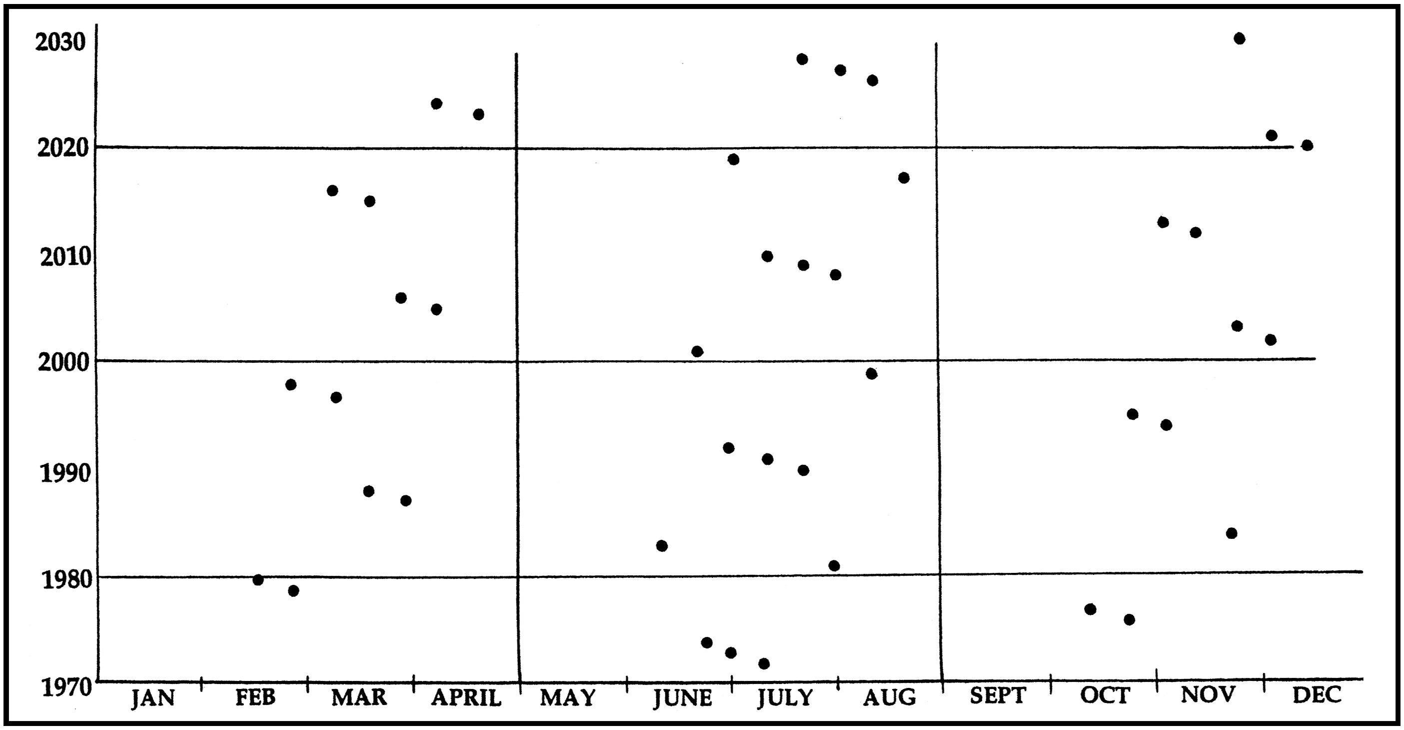


Fig. 66 Total solar eclipses by month and year from 1970 through 2030 A.D. Note the 18.03 year *Saros* cycle, after which time Moon, Sun and Earth return to almost identical positions relative to each other. At present, 12 total solar eclipses occur during a *Saros* cycle of 18.03 years.

particularly the time interval between eclipses, might be associated with far higher than normal tides?

In general, the average gravitational effect of the Sun is about 46 percent that of the Moon; however, in the Bay of Fundy the effect of the Sun is only about 15 percent that of the Moon. Further, because the orbits of the Earth around the Sun and the Moon around the Earth are elliptical, and their paths influenced by many factors (Fig. 67), the gravitational effects are variable in strength, like tides (House 1995).

Normal tides are termed astronomical tides because their main variations are generated by three astronomical phenomena as noted earlier: the variable distance between the Moon and Earth; the variable positions of the Moon, Sun and Earth relative to each other; and the declination of the Moon and Sun relative to the Earth's equator. Additional astronomical factors that influence tides include: the Earth's rotation; the eccentricity of the Moon's orbit, which varies depending on the Sun's position in relation to the longest axis of the Moon's orbit.

Non-astronomical phenomena include: the possible increasing tidal range in places like the Bay of Fundy due to deepening waters (Godin 1992); atmospheric disturbances; the geometric shape of inlets, bays and ocean basins; the postglacial rise in sea level (see Fig. 68). This last factor, by no means trivial, translates to about a world-wide 2 mm/yr submergence of the land in relation to sea level (Schneider 1997).

11.3. THE LARGEST ASTRONOMICAL TIDES

As seen from Earth, the Moon and Sun seem to move within two imaginary rings around Earth's centre (Fig. 69). The ring in which the Moon's motions are confined has an outside diameter of 813 000 km and a maximum thickness of 50 000 km, while its width varies during an 18.61 year period between 410 000 km and 255 000 km. The Sun appears to move within a similar ring, with an outside diameter of $3.04 \cdot 10^8$ km, a maximum thickness of $5 \cdot 10^6$ km, while its width remains constant at $1.25 \cdot 10^8$ km. At perigee the distance to the Moon is $3.57 \cdot 10^5$ km, and at apogee the distance is $4.07 \cdot 10^5$ km.

The positions of the Sun and Moon in their respective (elliptical) orbits, and in relation to each other and the Earth, are only occasionally repeated. When one position is inducive to generating large tides, an approximate date for a repeat performance can be determined by matching the several types of astronomical months. Such months are designated as synodic, anomalistic, tropical, nodical or evectional, according to whether the revolution of the Moon around the Earth is relative to the Sun's position, the shortest distance to the Earth, its passing through the Earth's equator, its passing through the ecliptic, or the variation in the eccentricity of its orbit. For some months, such as the synodical (full and new moon), tropical, and nodical, the characteristics influencing the tides occur half-monthly. Since the synodical conditions provide the

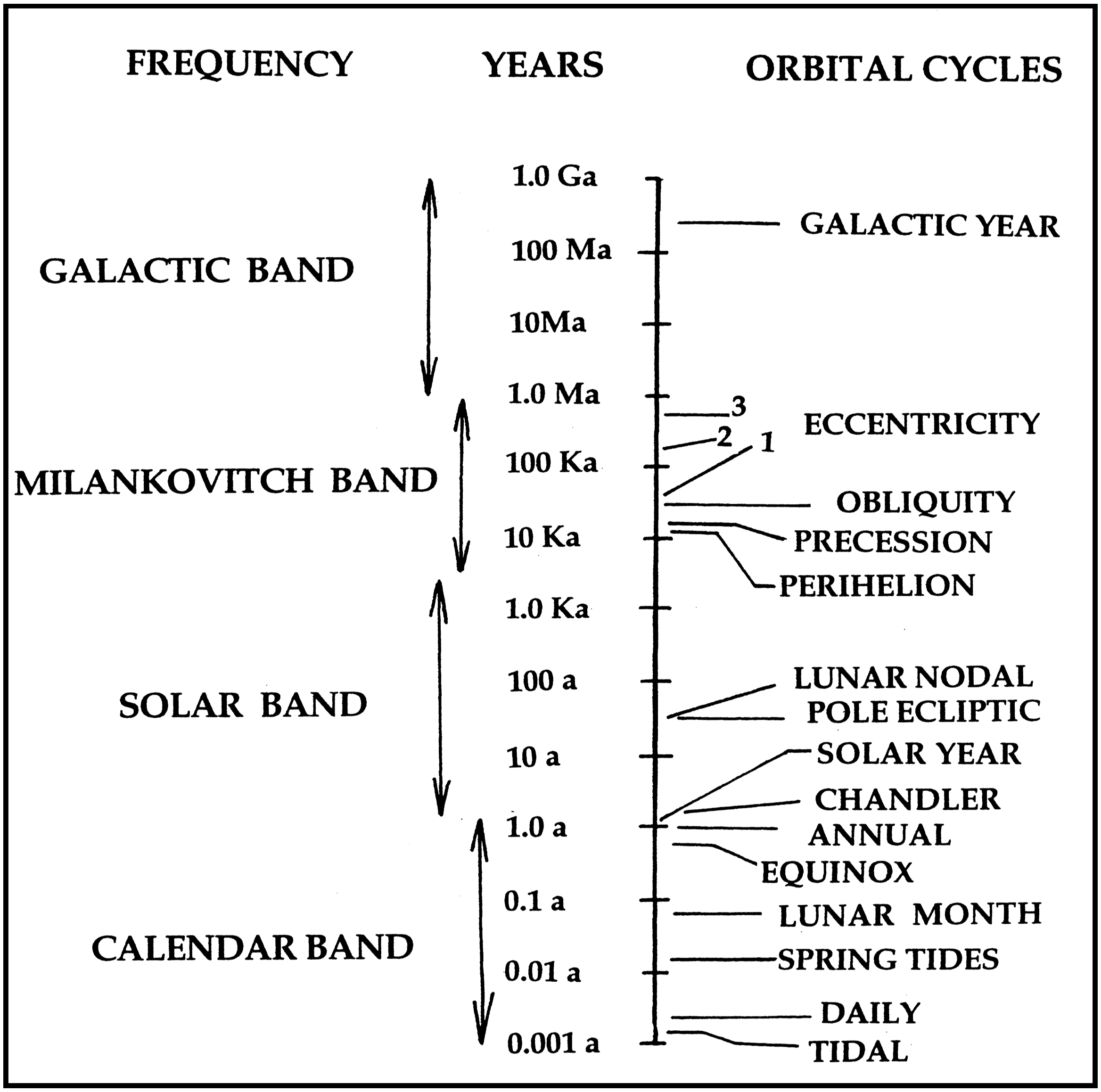


Fig. 67 Orbital forcing time scales (logarithmic) of tidal cycles is only a small portion of the spectrum of astronomically-driven periods which exert gravitational effects on Earth and human affairs. Modified from House (1995).

dominant tidal conditions, one can expect two sets of spring tides during one synodical month. But when one of these sets coincides with the Moon's closest approach to the Earth, extra high (perigean) spring tides will occur.

It takes 29.531 solar days between one new moon and the next. However, only 27.555 solar days (anomalistic month) elapse from the time that the Moon is closest to the Earth, to the next such occasion during the Moon's elliptical orbit around Earth. When the Moon is in perigee, and its phase is either full moon or new moon, one can expect the strongest tides. However, as the periods of both movements are not the same, the coincidence of such occurrences is only periodic.

Imagine a racetrack. On this track are two cars, marked N and F. They always move half a track apart around the raceway. Let the raceway be 360° long. Thus, each day, these cars move 360°/29.531 = 12.19°/day (V). Another car, marked P, starts at the same time beside car N, but its velocity is 360°/ 27.55 = 13.06°/day (W), thus somewhat faster than car N. In time, car P will overtake car F, which was 180° in front of car N. The time it will take to close this gap can be calculated (approximately) as 180/(W–V) = 205.892 days.

The same applies to lunar movements. After about 206 days, the conditions for stronger than average tides recur, perigee coinciding either with new moon or full moon. Two of these periods are 411.78 days long. Thus, each year one can expect the conditions for stronger tides to be (411.78–365) = 47 or 46 days (leap year) later than in the previous year.

The declination of the Moon also has an influence on the strength of the tides on particular days. This declination has its strongest values twice in a period of 27.321 solar days (tropical month) with a velocity of 360°/27.32 = 13.18°/day. This is somewhat faster than the velocity of the perigee. Therefore in order to have the coincidence of a similar combination between perigee and declination of the Moon, it will take 1615.75 days, or 4.42 years. Should a particular part of the declination cycle cause somewhat higher tides then the coincidence with perigee will repeat after 4.42 years. During the *Saros* cycle of 6585.32 days, there will be 238.997 perigee cycles, 446.01 (full moon-new moon) cycles, and 482.07 declination cycles.

The most favourable combination of factors to produce strong tides in the Bay of Fundy occurs when perigee coincides with spring tide at the very time that anomalistic, synodic and tropical months peak simultaneously. As it happens (see Table 22), the best match occurs after a period of 6585.3 days (18.03 years). The driving mechanism of this cyclic phenomenon is the same one that orders the timing of eclipses – the *Saros*.

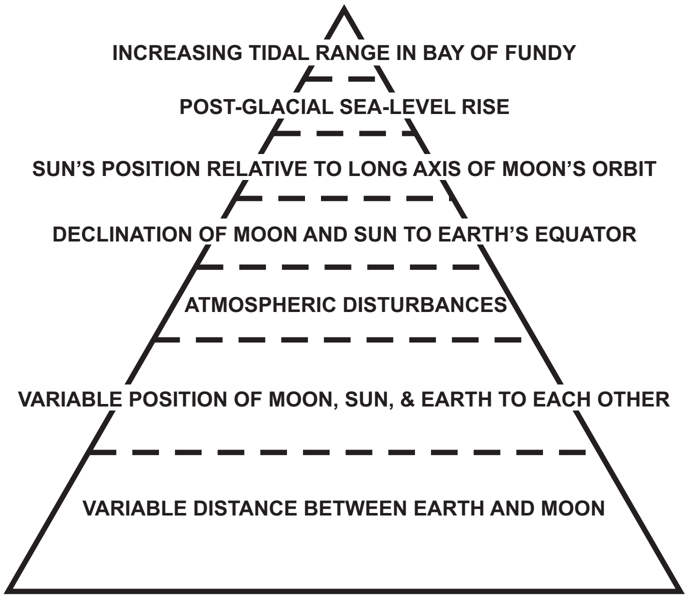


Fig. 68 **Triangular diagram shows the relative importance of the main astronomical and non-astronomical phenomena that contribute to the generation of storm tides in the Bay of Fundy.**

11.4. COINCIDENCE OF STORM TIDES WITH *SAROS*

Given the clockwork precision of astronomical conditions and their absolute control over *normal* tide variations it is rea-

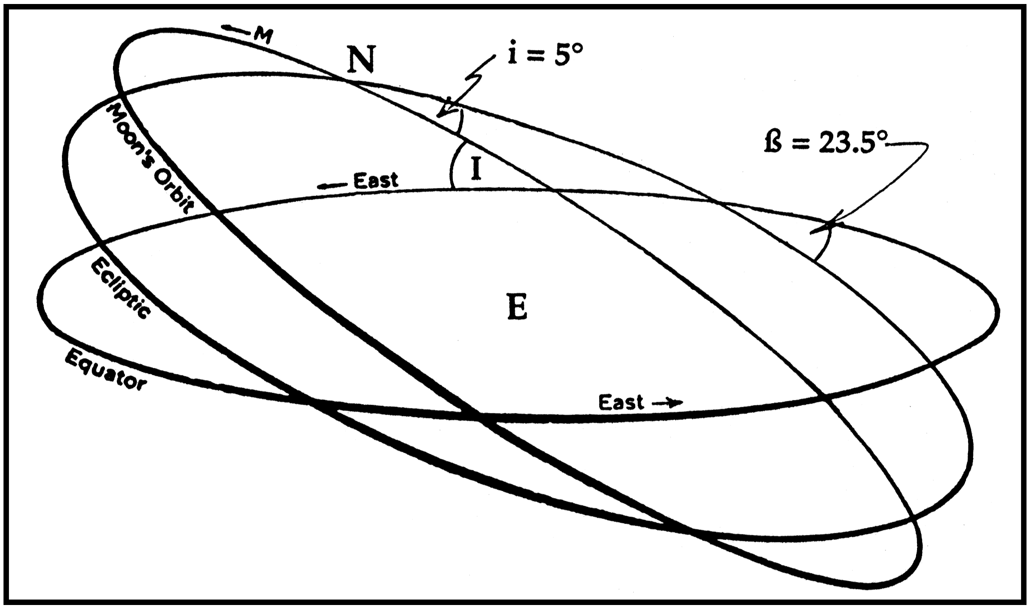


Fig. 69 **This diagram indicates the variation in the obliquity of the Moon's orbit during the nodical lunar cycle, completed in 18.6 years; this introduces an important inequality in tidal movements. The angle β, between the ecliptic and the celestial equator (the obliquity of the ecliptic) has a nearly constant value of 23.5°. Angle i, between the ecliptic and the plane of the Moon's orbit has a value of about 5°. Angle I, the obliquity of the Moon's orbit, measures the inclination of the Moon's orbit to the celestial equator. Its magnitude changes from 18.5° to 28.5°, with the position of the Moon's node. When the Moon's ascending node N, coincides with the vernal equinox, I = β – i = 18.5°. After Schureman (1941, p. 6).**

sonable now for us to enquire whether the Saxby Tide, and for that matter other historical storm tides in the Bay of Fundy, coincided with the *Saros*.

What are the chances of a periodic storm system on the scale of the Saxby tide? The only certainty is that the relationships between the Moon and the Sun that produce the highest tides on Earth are repeated in the same periods as those that create solar and lunar eclipses (Abell *et al.*1988), namely the *Saros* cycle of 18.03 years. Therefore, to check the position of an historical high tide in the *Saros*, one need only add to the tide's date the appropriate multiple of the *Saros* (Table 23) to reach a particular time interval for which the tidal record is well known. Detailed tidal records in Canada were first kept about 1894. So as a reference point let's choose a date close to the end of 1958, which is eleven *Saros* after the Saxby Tide. The tidal levels referred to are those measured at Saint John, where the average high tide is 7.7 m (25.2 feet) above CD. To test the reliability of the method of prediction, our examples of historical storm tides can now be checked against predicted tides, *n Saros* cycles later.

Checking the multiples of the *Saros* against storm tides, we discover that the storm tides of 1759 and 1869 correlate very closely with *predicted* high tides of the *Saros* cycle (Table 24). So do the 1976 Groundhog Day storm, and the exceptionally High Water of 12 October, 1887, experienced in Moncton, and the storm tides of 20–22 December, 1995 (Taylor *et al.* 1996). However, it is important to bear in mind through any exercise of this type that *Saros* cycles are long term harmonic motions. This means that near the top or bottom of the cycle the rate of change with time is relatively small. Thus, the "peaks" of *Saros* cycles are not confined to points in time, but to rather short intervals of time.

Table 22. Long term cycles of astronomical conditions leading to stronger or weaker than normal tides

Anomal. month 27.5546 days	Synodic. month 29.5306 days	Tropic. month 27.3216 days	Nodical month 27.2122 days	Evection period 31.8119 days	Stand. dev. days	Gregor. year 365.24 days	Eclipse year 346.62 days
Number of months or years							
Number of solar days							
7	6.5	7	7	6		0.528	0.556
192.88	191.95	191.25	190.49	190.87	1.63		
15	14	15	15	13		1.131	1.192
413.32	413.43	409.82	408.18	413.56	3.49		
60	56	60.5	61	52		4.526	4.769
1653.27	1653.71	1652.95	1659.95	1654.22	2.90		
112	104	113	113.5	97			
3086.11	3085.95	3087.34	3088.59	3085.76	1.20		
172	160	173	174	149		12.975	13.673
4739.38	4739.66	4740.29	4734.93	4739.98	2.22		
239	223	241	242	207		18.030	18.999
6585.54	6585.32	6584.50	6585.36	6585.07	0.40		
299	279	301.5	303	259		22.557	23.768
8238.81	8239.03	8237.46	8245.30	8239.29	1.35		
351	327	354	355	304		26.480	27.902
9671.65	9671.27	9671.84	9673.94	9670.83	1.20		

Notes. Anomalistic month (cycle of perigean tides) = 27.555 days; synodic month (cycle of Moon's phases in which there are two sets of spring and neap tides) = 29.531 days; tropical month (cycle in which Moon crosses the Equator twice) = 27.322 days. Close match between multiples of anomalistic, synodic and tropical months coincides with repeated similar tidal conditions. A close match between synodical and nodical months are cycles for lunar and solar eclipses. (After Desplanque and Mossman, 1998a)

11.5. PROBABILITY OF A REPEAT OF THE SAXBY TIDE

Whether property owners along the Bay of Fundy should be reminded of their next appointment with the *Saros* in 2012–2013 AD is not trivial question (Fig. 70). With increasing encroachment of people in coastal zones, the risk of loss of life and major property damage in the Gulf of Maine-Bay of Fundy region is substantial in the event of a tide like the Saxby Tide (Shaw *et al.* 1994). Simply put, what is the probability of a storm tide coinciding with a large astronomical tide? We can conveniently address this question using the above examples. We know that a "peak" of the *Saros* occurred between 6 March, 1958, and 31 December, 1959. During this time, there were 1288 tides at Saint John, 37 of which were extreme astronomical high tides (28.5 feet or higher). Thus, the chances that an historically memorable storm tide coincided with one of the 1288 tides, is slightly less than 3 percent. This is assuming that the occurrence of stormy weather conditions is spread evenly throughout the year. The increased incidence of high winds during late spring and fall probably favours the odds of gale force conditions coincident with high tides slightly above 3 percent.

Most assuredly, postglacial sea-level rise is a significant factor in all this. With each and every repeat of the *Saros*, an increase of the high tide mark of at least 3.6 cm (2 mm/year for 18 years) can be expected. Thus, since the Saxby Tide more than seven *Saros* ago, sea level has risen eustatically nearly 25 cm. Added to the minimum 1.5 m by which the Saxby Tide exceeded high astronomical tides, a height is calculated that that is more than sufficient to overrun the present dyke system.

It seems likely that tides like the Saxby might be recurrent, although one wishes for a larger database. The clockwork precision of astronomical conditions exerts absolute control over normal tidal variations. But there remains much to learn about long term periodic events associated with tides and the weather. We have seen that only significant storms coincident with large tides, or extraordinarily severe storms coincident with medium tides, can result in higher tide marks than are reached by astronomical tides alone. Detailed tidal records over several decades show that in the Bay of Fundy there is a tendency for slightly higher maximum monthly High Water marks in a 4.5 year cycle, examples being the peaks that occurred in 1998 and 2002. Indeed, in this region, high perigean tides levels can be anticipated at intervals of 1 month, 7 months, 4.5 years and 18 years. When such high tide levels coincide with severe atmospheric disturbances, exceptionally High Water surfaces can be expected. However, short of an extraterrestrial catastrophe, they are not likely to attain the 120-foot (36.6 m) height of legend. Property owners along the Bay of Fundy should nevertheless keep in mind their next appointment with the *Saros* in 2012–2013.

Table 23. Multiples of the Saros

Saros	Years	Days
Cycle 1	18	11
Cycle 2	36	23
Cycle 3	54	34
Cycle 4	72	45
Cycle 5	90	57
Cycle 6	108	68
Cycle 7	126	79
Cycle 8	144	91
Cycle 9	172	102
Cycle 10	180	113
Cycle 11	198	125

Table 24. Countback of tides in the Bay of Fundy at 18.03-year intervals

Comparison of the 1759 storm tide with the high tide at Saint John eleven *Saros* cycles later, on 8 March 1958:

	Date	Year	Day in the year
Historical high tide	3 November 1759	1759	307
Add 11 *Saros* cycles (198 years 125 days)		198	125
		1957	432 (1 yr 67 d)
		8 March 1958	

The predicted high tide for 8 March 1958 was 8.75 meters.

Comparison of the Saxby Tide, 1869, with the high tide at Saint John five *Saros* cycles later, on 1 December 1959:

	Date	Year	Day in the year
Saxby Tide	5 October 1869	1869	278
Add 5 *Saros* cycles (90 years 57 days)		90	57
		1959	335
		1 December 1959	

The predicted high tide for 1 December 1959 was 8.84 meters.

Notes. Calculations show that the historical storm tide of 3-4 November 1759 and the Saxby tide of 4-5 October 1869 closely coincide with predicted high tides of the Saros.

Fig. 70 Crossing the Tantramar Marsh during High Water, spring tide, 9 November, 1980, looking northwest from Aulac, N.B. The closest *Saros* date was 12 December, 1978, a year of many high waters. Photo by Elly Desplanque.

12. Tidal Boundary Problems in the Coastal Zone

12.1. INTRODUCTION: CAVEAT EMPTOR!

The need for precise determination of tidal water boundaries stems from numerous concerns, including cadastral surveying, coastal property evaluation, development of offshore resources, protection of fisheries, and ownership of the foreshore and sea bed (Nichols 1983; Daborn and Dadswell 1988). Historically, the dividing line between wet and dry land, or as far as the tide ebbs and flows, has been critical in resolving tidal boundary problems in the coastal zone (Ketchum 1972). However, the location of the mean high water line has been a matter of considerable litigation (Greulich 1979; Desplanque 1977). What exactly is this dividing line, and how can levels like Mean High Water and Mean Low Water be most accurately defined?

Presumably, Mean High Water is reached under mean astronomical conditions, with perhaps some long-term tectonic and climatological influences to be considered. Climatic influences in Atlantic Canada tend to raise the water during the winter months, so that in areas of relatively small astronomical tides along the Atlantic seaboard the frequency of extreme high observed water levels is higher during that season. However, astronomical influences are variable and follow cycles in which the magnitude of influences waxes and wanes (Schureman 1941). The longer the cycles, the greater the variation. In the Fundy region, as discussed earlier (section 11.0), distinct cycles are recognized (Desplanque and Bray 1986).

Meteorological influences can raise or lower water surface levels over a period of days, during which time High Waters and Low Waters are similarly affected. On a year long scale, climatic influences in the Atlantic region tend to raise the water level during winter months. Thus in areas of relatively small astronomical tides along the Atlantic coast of North America the frequency of extreme high observed water levels is higher during winter. The eustatic rise of sea level can not be neglected in these considerations: over the course of an 18 year cycle, accepting a global average 2 mm/yr eustatic rise in sea level (Schneider 1997), water level will have risen by about 3.5 cm. In view of the above considerations it appears that decisions handed down in courts of law on issues concerning tidal water boundaries are in many cases equivocal (Nichols 1983; Desplanque 1977).

Harvey *et al.* (1998) provided a very interesting analysis of the legal and policy framework concerning the restoration of the habitat of Fundy estuaries. Unfortunately, important overlapping boundaries of provincial and federal jurisdiction, in some cases unresolved, seem to have resulted in poorly regulated environmental protection. Details of the many issues of territorial and legislative jurisdiction, as they generally concern Bay of Fundy waters and the coastal zone, are beyond the scope of this paper. Nevertheless many of the key issues center on the problem of establishing specific water level boundaries.

12.2. MEASUREMENT OF TIDAL LEVELS

Concerning the tide levels and terms used in Canada (as set out in section 2.1), all tidal measurements are made from the local Chart Datum (CD). The International Hydrographic Bureau recommends that CD at a certain location should be at an elevation so low that the tide at that place will seldom if ever fall below it. The reason for this recommendation is that the soundings on hydrographic charts will show the minimum depth of water with which mariners will need to deal. The tidal range gives them an extra margin of safety. Generally tidal range is small and so is this factor in their margin of safety. However, on Bay of Fundy charts showing a number of tidal stations, the difference between CD and Mean Water Level (MWL) in one section of the charted area may be quite different than it is in other sections. The soundings on such charts do not allow one to construct a proper three-dimensional picture of the shape of the Bay.

The Canadian Marine Sciences Branch defines *mean sea level* (MSL) as the level that oceanic water would assume when no atmospheric, hydrologic or tidal influences act upon it. They also use the term Mean Water Level (MWL), which is the sea level resulting in the absence of tidal influences. Up to certain limits the base level of the tides is moving up and down with the water level caused by atmospheric and hydrologic conditions. Since it is easier in the field to establish a local MSL or MWL than a level indicating the Mean High Water Mark (MHW), it is recommended that MHW be the level reached by the M_2 amplitude above MSL.

It is worth noting too that whereas the Canadian Tide and Current Tables give the values of tidal differences for Higher High Waters and Lower Low Waters, the U.S. Tide Tables give the values for Mean High Water (MHW) and Low High Water (LHW). Consequently, the values of the ranges for mean and large (spring) tides differ greatly in both tables for the same locations (see Table 25). The differences between these datums are significant to the problem of establishing tidal boundaries. Canada apparently lacks a definition of MHW, a level usually taken in surveying practice as equivalent to “Ordinary” High Water (OHW) (Nichols 1983). Britain’s intertidal zone is also proving difficult to map due to use of different vertical scales by Ordnance Survey and the Admiralty’s Hydrographic Office, and the fact that the latter organization uses “the lowest astronomical tide” as zero point for depth (Tickell 1995). The Americans take MHW as the average of all the High Water heights observed over the National Tidal Datum Epoch. For this reason American definitions are inappropriate for direct use in Canada.

Next let's examine how an accurate determination of the Mean High Water mark can be made.

12.3. TIDE PREDICTION: MEAN SEA LEVEL AND MEAN HIGH WATER

For most locations (ports) along the Canadian sea coast, the M_2 tidal constituent is dominant. In fact the amplitude of the M_2 tide very closely represents the average tidal conditions. When measured above the local MSL, it will indicate the level of MHW. The value of this amplitude has been determined for a great many ports along the Canadian sea coast. As for MSL, it can be easily determined by taking the average of hourly readings in calm conditions over one lunar day. The mean of these readings should indicate the MWL of the day. In order to verify if this level is close to MSL one can check at the nearest tidal recording station if the observed tides for that day correspond closely to the predicted ones. If so, the MWL can be used as a substitution for MSL. Otherwise a correction can be made by applying the difference to the measured value of MWL. Generally these differences (when they occur) are in the same order of magnitude for a number of recording tidal stations.

Since the Higher High Water (HHW), the Lower High Water (LHW), and the MWL values (see Table 26) above local CD are determined for a great number of stations along the eastern seaboard, the Mean High Water mark for most locations can be accurately determined with very little effort. A large degree of accuracy is not warranted because the landmass of the southern part of the Atlantic Provinces is steadily submerging at a rate matched by the rise of the High Water mark.

12.4. THE WATER'S EDGE: CONFUSION IN LEGISLATURE AND LITERATURE

As expressed in Canadian law, "The land on the seaward side of the high water mark is *prima facie* held by the sovereign in common law jurisdictions." In other words such land is generally owned by the state, i.e., in Canada, the provincial or federal government.

Some Nova Scotia acts, for example, reflect this principle (Kerr 1977). The 1967 Nova Scotia Beach Protection Act states that the Governor in Council, on recommendation of the Minister of Lands and Forests, may designate as protected beach, an area which "...may include the land extending seaward from mean high water mark and such land adjacent thereto ... The Minister of Lands and Forests may post signs on or near land of the Crown extending seaward from mean high water mark, warning the public that the beach is protected under this Act".

The 1975 Nova Scotia Beaches Preservation and Protection Act declares that "beach" means that area of land on the coastline to the seaward of Mean High Water mark, and that land landward immediately adjacent thereto, to the distance determined by the Governor in Council.

The 1949 Nova Scotia Marshland Reclamation Act interprets as "marshland" the land lying upon the sea coast or upon the bank of a tidal river, and being below the "level of the highest tide". Legislative practice assumes that the vertical and horizontal location of the Mean High Water mark, and the level of the highest tide are established and available all along the coastline. Unfortunately, confusion abounds in legal circles about the characteristics of the tides and the terminology used to describe them. For instance, in the upper reaches of the Bay of Fundy the tides can reach more than 8 m above MSL during strong tides, whereas during weak tides the High Water is scarcely 3 m above that level. Approximately 50% of the tides reach above the 5.5 m mark. Furthermore, the range varies from year to year and from location to location along the coast. Complicating matters is the fact that MSL changes even in the short term (Fairbridge 1987), at different rates in relation to the landmass, depending upon the location. Indeed, the concept of MSL is like Earth's Magnetic North Pole, elusive. Thus, in tide tables, the term Mean Water Level is used.

The confusion in legal circles is exemplified in "Water Law in Canada-The Atlantic Provinces" (La Forest 1972) where the three types of tide of which the law takes cognizance are described:

Tide type #1 – high spring tide, which occurs at the two equinoxes;

Tide type #2 – spring tide, which happens at the full moon and the change of the Moon;

Tide type #3 – the neap, or ordinary tide, which takes place between full moon and change of the Moon, twice every twenty-four hours.

Table 25. Comparison of Canadian and American Tide Tables (1975) of tidal ranges for the same six selected ports

	Canadian Tables		U.S. Tables		
(All units in feet)	Mean	Large Tides	Mean	Spring Tides	M_2
Saint John, NB	21.9	30.0	20.8	23.7	10.09
Burntcoat Head, NS	39.1	52.6	38.4	43.5	18.51
Halifax, NS	4.7	6.9	4.4	5.3	2.07
North Sydney, NS	3.1	4.7	2.6	3.2	1.23
Pictou, NS	4.0	6.4	3.2	3.9	1.40
Charlottetown, PEI	6.0	9.6	5.2	6.4	2.33

Notes. Values for M_2 tidal constituent are taken from "Harmonic Constants and Associated Data" of the Canadian Marine Sciences Branch, 1969.

Table 26. Mean tide levels at several Atlantic Canada ports illustrating the contribution of semidiurnal and diurnal constituents

	Mean Tide Level above local Chart Datum			Mean Tide Level above Mean Water Level			Tidal Constituent	
(All units in feet)	HHW	LHW	MHW	HHW	LHW	MHW	M_2	K_1
Saint John, N.B.	25.1	24.2	14.3	10.8	9.9	10.35	10.09	0.50
Yarmouth, N.S.	13.8	13.0	7.9	5.9	5.1	5.5	5.35	
Halifax, N.S.	6.4	6.0	4.1	2.3	1.9	2.1	2.07	0.34
North Sydney, N.S.	4.6	4.2	3.1	1.5	1.1	1.3	1.23	
St. John's, Nfld.	4.0	3.4	2.5	1.5	0.9	1.2	1.16	0.25
Pictou, N.S.	5.6	4.9	3.7	1.9	1.2	1.55	1.40	0.68
Charlottetown, P.E.I.	8.0	7.4	5.3	2.7	2.1	2.4	2.33	0.84
Shediac Bay, N.B.	3.9	3.4	2.8	1.1	0.6	0.85	0.65	0.84
Rustico, P.E.I.	2.9	1.5	1.6	1.3	-0.1	0.6	0.55	0.60
Pointe St. Pierre, Que.	4.3	2.8	2.4	1.9	0.4	1.15	1.16	0.63

Notes. At ports where the semidiurnal constituent M_2 is dominant, the height of MHW is only a few hundreds to a few tenths of a foot higher than the height of M_2 above that level. Where the diurnal tide K_1 is dominant, as in Shediac Bay, N.B., and Rustico, P.E.I., this constituent governs the mean tide height. (Data from v. 1 and 2 of Canadian Tide and Current Tables for the Atlantic Coast, Bay of Fundy and Gulf of Saint Lawrence and the 1979 Manual of the Tides and Water Levels Section of the Canadian Hydrographic Service)

Unfortunately, because of three reasons discussed in the ensuing paragraphs, it is doubtful whether these types of tide have any significance along the eastern and western seaboards of the North American continent.

Firstly, Pliny the Elder (23–79 A.D.) observed that the tides appear to be the strongest in the periods close to the equinoxes, namely on 21 March and 23 September. This observation may well be true for tides along the eastern side of the North Atlantic Ocean. However, Pliny could not know that the conditions along the American coastline are different. Thus, Table 27 shows that although tides on the eastern side of the Atlantic are highest near the equinoxes, this is clearly not the case for tides along the eastern or western coastlines of North America. Note that the tides in 1953 and 1975 on the eastern seaboard of North America may reach their highest levels at any month of the year due to their advance by 47 or 46 days each year as a result of perigee coinciding with either new moon or full moon. The definition of tide type #1 implies that equinoctial tides are in a way special, but this rule is in no way universal.

Secondly, the term "change of the Moon" is archaic, and designates new moon. It means, simply, that tides occurring during the period that the Moon appears in its full moon and new moon phases are stronger than average tides. This is of course due to the fact that these phases of the Moon occur when the Earth, Sun and Moon are most closely aligned. At these times, the gravitational action of the Sun reinforces the action of the Moon, resulting in higher than average tides, just as is supposed to happen in type #1 tides. During its orbit, the Moon is in one of its two quarter phases when halfway between its new moon and full moon positions. At such times the gravitational action of the Sun counteracts the dominant Moon's action, resulting in neap tides.

Unfortunately, in legal circles European tidal conditions are taken as standard and assumed to be universal. Theoretically the Sun's action is close to 46% of the Moon's gravitational influence. However, when the tides are analyzed, the actual percentage can differ depending upon the locality. Some of the measured percentages on the east side of the Atlantic Ocean are: Casablanca 37%, Rabat 40%, Lisbon 39%, St. Nazaire 35%, Flushing 27%, Bremerhaven 25%, London 27%, Liverpool 32%, Kingstown 30%. These figures are the ratios between the local tidal constituents S_2 and M_2 (Schureman 1941). Note that these percentages are smaller than the theoretical one. Nevertheless, they are relatively strong compared to those along the North American eastern seaboard south of Sable Island. Here the percentages are 20% or even less (15%) in the Bay of Fundy. This diminished strength of the Sun-caused tides means that the term "spring tide" loses much of its significance. In the Bay of Fundy the varying distance between Earth and Moon is the most important factor in determining

Table 27. Highest monthly tides at ports along eastern and western coastlines of North America, and the eastern side of the North Atlantic Ocean in 1953 and 1975

Year	J	F	M	A	M	J	J	A	S	O	N	D
Lisbon, Portugal												
1953	1.80	1.95	1.98	1.89	1.74	1.65	1.86	2.01	2.04	1.95	1.80	1.74
1975	1.95	2.01	1.95	1.83	1.71	1.65	1.71	1.92	2.07	2.10	1.95	1.92
Liverpool, England												
1953	4.33	4.63	4.57	4.30	3.72	3.75	4.21	4.60	4.60	4.33	3.81	3.57
1975	4.94	5.03	4.88	4.48	4.18	4.08	4.51	4.88	5.03	4.69	4.72	4.42
Halifax, Canada												
1953	0.98	0.98	1.01	0.94	0.91	0.82	0.85	0.94	1.01	1.10	1.04	0.94
1975	1.07	1.07	1.04	0.98	0.88	0.85	0.88	0.94	1.01	1.07	1.07	1.04
Saint John, Canada												
1953	3.99	4.27	4.33	4.30	4.05	3.72	3.99	4.15	4.30	4.36	4.15	3.81
1975	4.18	4.30	4.30	4.33	4.08	3.78	3.96	4.18	4.30	4.42	4.39	4.18
New York, U.S.A.												
1953	0.94	0.94	1.01	1.07	1.10	1.04	1.07	1.10	1.13	1.16	1.07	0.94
1975	1.01	0.98	1.07	1.13	1.10	1.04	1.07	1.13	1.13	1.19	1.16	1.07
Vancouver, Canada												
1953	1.83	1.71	1.52	1.43	1.52	1.62	1.62	1.52	1.43	1.31	1.52	1.62
1975	2.04	1.89	1.74	1.55	1.62	1.80	1.86	1.80	1.71	1.55	1.68	1.74
San Francisco, U.S.A.												
1953	1.07	1.01	0.88	0.94	1.01	1.04	1.04	0.98	0.94	1.04	1.10	1.10
1975	1.07	0.98	0.91	0.98	1.01	1.04	1.01	1.04	0.94	1.01	1.07	1.10

Notes. Heights in metres above mean water level. Note that highest tides are not necessarily equinoctial. (After Desplanque and Mossman, 1998a)

tidal strength. Perigean spring tides are outstanding, while apogean spring tides hardly differ from average tides. Thus, the importance otherwise given to the term "spring tide" shows that tidal phenomena around the North American continent are not very well understood in legal circles.

Thirdly, the term "neap, or ordinary tide ... which takes place ... twice every twenty-four hours ..." is a very confusing expression. For example, the period of 24 hours is not very precise because in most cases, the tides occur on average twice in a period of 24.84 hours, the lunar day. However, it is the term "neap or ordinary" that presents difficulty with respect to definition.

The term "High Water of Ordinary Spring Tides" is used in some British publications. The U.S. Coast and Geodetic Survey Tide and Current Glossary (1999) mentions that the term "ordinary" is not used in a technical sense by the Survey, but that term, when applied to the tides may be taken as equivalent to the terms "mean" and "average" (ASCE 1962). Thus, from that service's point of view the "ordinary tide" would be the same as the "mean tide". However a neap tide is a tide weaker than a mean or average tide. Thus the term "... the neap or ordinary tide ..." is a contradiction in terms.

Tide type #3 is correct insofar as this tide takes place between full moon and the "change of the Moon" (new moon), and presumably is the weakest possible. However, the term "ordinary", has various meanings, one being "of common or everyday occurrence", another being "average or mean" (La Forest 1972). However, when a condition is variable, it is not possible for that condition to also happen all the time, yet be the average condition. It is also true that all tides equal to or greater than the neap tide will attain a certain common level. It could be argued that a neap tide is an ordinary tide. However, it certainly will not be a mediocre, medium, mean, normal, or average tide. In this case the weakest possible tide is set as a standard. No mention is made of the variability of the distance between the Moon and Earth although this is an influential cause of tidal variability, and of high tides, and can equal or exceed the effect of the changing phases of the Moon.

In order for true diurnal tide conditions to exist, the amplitude of the diurnal tide must be two to four times larger than the semidiurnal tide, depending on the time relationship between the two. However, under certain astronomical and oceanographic conditions, tides may vary from diurnal to semidiurnal during a span of little over a day. Thus only one tidal oscillation sometimes occurs in the southern parts of the Gulf of St. Lawrence and in Northumberland Strait. This is due to an extreme case of diurnal inequality when the Moon has the greatest degree of declination and the local semidiurnal components of the tide are weak. As the Moon is in its greatest declination when the Sun is near the solstices, diurnal inequalities are the most prominent during the summer and winter months. Another expression of tidal diurnal inequality, prevalent in the Bay of Fundy (Desplanque and Mossman 1998a) is the sequence of Higher High Water–Lower Low Water–Lower High Water–Higher Low Water (see section 5.3.3). This sequence can also be reversed. Other conditions are two High Waters of equal elevations, and two unequal Low Waters (for example, Northumberland Strait) and of two equal Low Waters, but unequal High Waters as observed along the eastern shore of New Brunswick and the north shore of Prince Edward Island. These types of tides are evidently not recognized in legal circles.

12.5. *DE JURE MARIS*

Clearly the three types of tides, recognized by law, make little sense and can cause a great deal of confusion when applied in court decisions. The delineation and demarcation of boundaries in tidal zones becomes an impossible task when the courts assume conditions which are non-existent. Furthermore, the relative submergence or emergence of the landmass with respect to mean sea level is usually completely overlooked when decisions are made. Coastlines along the Bay of Fundy and southern Nova Scotia are generally submerging more rapidly than the global rise of sea level indicates (Shaw and Forbes 1990). Thus, MSL and also the high tide levels are rising at rates that vary 2 or 3 mm/yr to rates exceeding 8 mm/yr, as claimed for some coastal areas of Maine (Scott and Medioli 1979). In areas where beaches have a very gentle slope, such a rise can make a large annual horizontal shift of the High Water mark. Here the establishment of a permanent property boundary, based on the Mean High Water mark, is totally unrealistic.

The definition of the private-state boundary in common-law countries has its genesis in a 17th Century treatise, "*De Jure Maris*", by Sir Mathew Hale, chief justice of King's Bench, the highest court in England (Hale 1667). He devised the definitions of the three types of tides discussed above. Sir Mathew wrote his treatise in the same year that the 24-year old Isaac Newton conceived the idea of universal gravitation. At the time, Hale was the chief baron of the exchequer, and probably not yet knowledgeable of the new tidal theories that would follow from Newton's work.

Hale's private studies included investigations in classical law, history, the sciences and theology. He exercised considerable influence on subsequent legal thought. Small wonder, therefore, that his misconceptions on the nature of tides endure. A leading case in point was the precedent set in 1854 by the British decision "Attorney-General vs. Chambers". The facts of the case are not significant but the legal interpretation of tidal terms is particularly important for the Maritime Provinces of Canada. The court was asked to determine the legal rights of the parties, a matter which depended entirely upon the interpretation of the term "high water mark". In its decision the Court emphasized the significance of Hale's doctrine, noting that: "All the authorities concur in the conclusion that the right is confined to what is covered by "ordinary tides", whatever be the right interpretation of that word."

It is clear that the Lord Chancellor had problems with the term "ordinary". The Court defined the ordinary tides as: "... the medium tide between springs and neaps ... It is true of the limit of the shore reached by these tides that it is more frequently reached and covered by the tide than left uncovered by it. For about three days it is left short, and on one day it is reached. This point of the shore therefore is about four days in every week, i.e. for most part of the year reached and covered by the tides ... The average of the medium tides in each quarter of a lunar revolution during the year gives the limit of all usage, to the rights of the Crown on the seashore."

In other words, the High Water mark is calculated by averaging the medium high tide marks for each week in the lunar cycle during the year. It is clear that long term cycles such as an 18-year cycle, were not taken into consideration. Reference to Table 28 shows that this can result in different interpretations of the position of the High Water mark, depending on what year is taken into consideration.

12.6. BOUNDARY ISSUES

In common law, private ownership of land ends at the mean high water mark, and title to the area between the MHW and low water marks (so-called tidelands) is held by the sovereign states. In a leading U.S. Federal case, the United States Supreme Court referred to: "the mean high tide line which is neither the spring tide nor the neap tide, but the mean of all the high tides." Unfortunately, in other cases a different line is used, for example the vegetation line, the highest winter tide, and the mean higher high tide; a few states use the low water line as boundary (Bostwick and Ketchum 1972). Quite apart from the choice of tidal cycle, this lack of standardization bedevils tidal boundary issues on national and international scales. A long-term cycle was taken into account in the U.S.A. in the so-called "Borax" decision (United Sates Supreme Court 1935). In this landmark case in 1935, the United States Supreme Court ruled that "an average 18.6 years of tidal observations should be used to determine the datum elevation". Promoted in the U.S.A., this has been described as a progressive decision which incorporates the most accurate methodology for determining tidal boundaries. However the definition does not deal with submergence of the landmass in relation to mean sea level, difficulties in areas with diurnal or strongly mixed diurnal and semidiurnal tides, and non-tidal influences. Furthermore the 18.6 year cycle is based on the period of revolution of the Moon's nodes and during this period the diurnal inequality of the tides varies in strength.

The 1949 "Tide and Current Glossary" prepared for the U.S. Coast and Geodetic Survey defines MHW as "the average height of the high water over a 19-year period". For shorter periods of observation, corrections are applied to eliminate known variations and reduce the result to the equivalent of a mean 19-year value. The 19-year cycle, the so-called “Metonic Cycle”, was chosen because 235 lunations occur almost exactly in 19 mean solar years, and this is in step with the Julian calendar (Greulich 1979). Named for its discoverer, the Greek astronomer Meton (432 B.C.), this cycle was used by the Nicene Council in 325 A.D. to fix the date of Easter.

Unfortunately, in legal cases where tidal heights are important, the emphasis placed on cycles of 18.61 (and 19 years) may not be warranted. This is the case in regions like the Bay of Fundy where diurnal inequality of the tides is of such minor importance that it can be virtually ignored among variations caused by the coincidence of perigean and spring tides. Table 22 shows the situation with respect to long term cycles of conditions leading to stronger and weaker than normal tides. Note that if one used 246 anomalistic months (18.558 years), 247 anomalistic months (18.634 years), or 252 anomalistic months (19.011 years), the multiples of other types of months are not nearly as closely matched as with 18.03 years. Thus, the courts may easily be led astray by misapplying astronomical data.

In theory, the height reached at High Water is the full amplitude above MSL, which is defined as the level that oceanic water would assume if no tidal or atmospheric influences are acting upon it. On land, the datum used by geodesists, surveyors, and engineers, is the Geodetic Survey of Canada Datum (GSCD, or GD). This datum is based on the value of Mean Sea Level prior to 1910 as determined from a period of observations at tide stations at Halifax and Yarmouth, N.S., and Pointe au-Père, Québec, on the east coast, and Prince Rupert, Vancouver and Victoria, British Columbia, on the west coast. In 1922 this was adjusted in the Canadian levelling network. Because in most areas of the Maritime Provinces the landmass is submerging relative to MSL, geodetic datum drops gradually below Mean Sea Level. Thus, local MSL at present is about 280 mm (0.9 ft) higher than G.D. However, there is a dearth of data, and no one is certain what the exact difference is between GSCD and MWL at different stations. This situation is troublesome for engineers and biologists who need to know the proper relation between the two datums at particular places and it is no less likely to trouble legal minds.

12.7. DETERMINATION OF MHW, BAY OF FUNDY

A legal decision regarding tidal issues in the Bay of Fundy resulted from the 1962 to 1965 trial proceedings in the case of Irving Limited and the Municipality of the County of Saint John vs. Eastern Trust Company. This trial (for details see Desplanque and Mossman 1999a) highlighted a wholesale incorrect use of tidal data and definitions. Central to this case was the definition of Mean High Water (MHW). In brief, it transpires that no matter what is chosen as a MHW elevation, the value employed in the Irving case has no valid statistical basis.

In retrospect, it is instructive to consider the manner in which MHW (and HHW) vary according to the increased tidal range toward the head of the Bay of Fundy. This will be illustrated for the Minas Basin, where seven principal tidal constituents account for more than 90% of the total variability of the tides (see Table 3). Note that while the amplitudes of these semidiurnal tides increase toward the head of the Bay and Basin, the diurnal amplitudes remain virtually constant at 0.2 meters. The shallow-water tides are relatively small, but will certainly become large for locations within estuaries. No constituents are available for the tides within the estuaries. However the diurnal tides probably will not be altered when progressing into the estuaries. Semidiurnal amplitudes are clearly a function of the distance from the port of Saint John where the principal tidal hydrographic station is located. Thus as shown in section 5.3.2, the range of the dominant semidiurnal tides in the Bay of Fundy increases exponentially as they advance, at the rate of about 0.36% per kilometre. This allows local tidal range to be estimated very accurately, with reference to Geodetic Datum, from which follow realistic estimates of MWL and HHW.

The above relationship is, among other things, relevant to proposed tidal power schemes in the Bay of Fundy. These might very well modify the tidal regime (Greenberg 1987) and conceivably lead to international legal conflicts. Indeed a model used during the 1977 studies for Fundy tidal power development concluded that should a tidal power plant be built in the Minas Basin, the amplitude of average tides would increase by 0.15 m along the Gulf of Maine coastline of New England, and up to 0.25 m along New Brunswick coastline. Whatever the truth of this dire prediction, the fact is that coastal submergence is a reality that must be faced due to continuing sea-level rise. No protest, political or otherwise, can alter this situation. Further, if MHW is to be established, one has to make the choice between a permanent level linked to a certain year such as the Geodetic Datum of Canada, or a level which moves with changes in sea level due to geomorphological influences triggered by eustatic sea-level rise.

When the International Court of Justice set the boundary line between Canada and the United States through the Gulf of Maine, in October 1984, people on both sides of the border protested that the Court had decreased the area of the Gulf of Maine to such a degree that many jobs would be lost in both countries. If that same Court has to make a decision about changing characteristics of the tides and water levels in the Gulf of Maine-Bay of Fundy system, our knowledge of these characteristics had better be able to stand up to close examination.

12.8. THE BOTTOM LINE

An interdisciplinary approach is needed in the matter of tidal boundary delimitation. However, whatever the roles of lawyers, surveyors and scientists, the terms MHW and MLW need to be unambiguously defined in accordance with modern tidal and astronomical principles and terminology. European tidal conditions taken as standard in legal circles are not universal and consequently do not permit recognition of various

Table 28. Height (in feet from local Chart Datum) of the largest predicted tides for each month from 1927 to the end of 1997 for the port of Saint John, New Brunswick

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.		Year	Next Saros cycle year
1927		26.2	26.9	27.6	28.2	28.4	27.6	26	26.7	27.4	28.2	28.5	27.9		28.5	(1945)
1928		26.4	27.5	28.4	(28.6)	28.1	27.6	27.6	26.1	26.5	28.2	28.4	27.9	FM	28.6	(1946)
1929		26.5	25.8	25.5	26.6	27.5	(27.7)	27.5	27.0	26.5	26.5	27.0	27.2		27.7	(1947)
1930	FM	26.7	26.7	26.6	26.5	25.9	26.3	26.7	(27.0)	(27.0)	26.9	26.2	25.3		27.0	(1948)
1931		26.4	27.1	27.4	27.7	27.8	25.9	26.6	27.3	27.6	(28.0)	27.7	26.9		28.0	(1949)
1932		26.2	27.0	27.8	(28.2)	28.0	27.1	26.2	26.1	26.8	27.0	27.7	26.8		28.2	(1950)
1933		26.4	25.8	27.0	27.7	(28.0)	27.9	27.1	26.9	26.4	27.1	27.7	27.8	NM	28.0	(1951)
1934		27.4	27.1	26.7	26.6	27.1	27.4	(27.7)	27.4	27.1	27.0	26.1	26.9		27.7	(1952)
1935	NM	27.8	28.1	28.1	28.2	27.8	27.0	27.7	28.2	28.4	(28.6)	28.0	27.0		28.6	(1953)
1936		27.4	27.7	28.3	28.3	27.8	27.1	26.2	27.0	27.6	(28.6)	28.0	27.2		28.6	(1954)
1937		26.5	26.7	27.7	28.4	(28.6)	28.3	27.4	26.9	27.1	28.0	28.4	28.3	FM	28.6	(1955)
1938		27.9	27.3	26.5	26.9	28	(28.2)	28.0	27.5	27.0	26.9	27.2	28.0		28.2	(1956)
1939	FM	28.2	28.3	28.1	28.0	27.3	27.9	28.2	(28.5)	28.3	28.2	27.8	27.3		28.5	(1957)
1940		28.0	28.2	(28.8)	28.6	28	26.1	26.9	27.6	28.1	(28.8)	28.2	27.1		28.8	(1958)
1941		26.8	27.6	28.2	(28.9)	(28.9)	28.2	27.4	27.9	27.9	27.9	28.8	28.4	NM	28.9	(1959) 11 May
1942		27.7	26.9	26.5	27.6	(28.7)	28.1	27.9	27.0	26.2	27.0	27.0	28.2		28.7	(1960)
1943	NM	(28.1)	27.9	27.3	26.9	27.2	27.8	27.9	27.9	27.8	27.3	26.9	27.4		28.1	(1961)
1944		28.0	28.1	28.0	27.7	27.1	26.1	27.3	27.8	28.0	28.1	(28.2)	27.1		28.2	(1962)
1945		26.8	27.7	28.1	28.3	28.6	27.8	26.8	27.2	27.9	(28.7)	28.6	27.9		28.7	(1963)
1946		26.0	26.0	26.9	27.9	(28.3)	(28.3)	27.4	26.1	26.1	27.1	28.0	28.1	FM	28.3	(1964)
1947	FM	(27.8)	27.1	26.8	27.0	(27.8)	(27.8)	27.6	27.1	26.9	26.5	26.0	27.0		27.8	(1965)
1948		(27.6)	27	27.3	27.1	26.4	26.3	26.9	27.4	(27.6)	(27.6)	27.5	26.6		27.6	(1966)
1949		26.9	27.6	28.0	(28.4)	27.9	26.9	26.5	27.4	28.0	(28.4)	28.0	27.0		28.4	(1967)
1950		26.0	26.5	27.3	28.2	(28.5)	28.0	27.1	25.6	26.8	27.9	28.2	28.0	NM	28.5	(1968)
1951		27.3	26.8	26.9	27.4	(27.6)	27.5	27.4	27.0	26.5	26.8	27.4	27.6		27.6	(1969)
1952	NM	(27.9)	27.6	27.1	26.9	26.4	27.0	27.5	27.8	27.8	27.8	27.2	26.6		27.9	(1970)
1953		27.6	28.2	28.4	28.3	27.5	26.4	27.3	27.8	28.3	(28.5)	27.8	26.7		28.5	(1971)
1954		26.1	27.2	28.0	28.7	(28.8)	27.8	25.9	26.7	27.7	28.4	28.6	28.0		28.8	(1972)
1955		27.3	26.7	27.7	28.4	(28.5)	28.1	27.5	26.5	26.1	27.0	28.2	28.4	FM	28.5	(1973)
1956	FM	28.0	27.5	26.9	26.9	27.6	28.1	(28.3)	28.2	27.8	27.4	27.1	27.9		28.3	(1974)
1957		28.4	(28.5)	28.3	28.0	27.1	27.5	28.1	28.4	27.4	27.5	27.3	27.0		28.5	(1975)
1958		27.3	28.1	28.7	(29.1)	28.9	28.0	26.8	27.6	28.5	(29.1)	29.0	28.3		29.1	(1976) 10 April
1959		26.6	27.5	28.6	28.7	(29.0)	28.4	27.5	26.6	26.9	28.0	28.8	(29.0)	NM	29.0	(1977) 22/24 May
1960		27.9	27.2	26.6	27.8	28.4	(28.6)	28.5	28.0	27.4	26.9	27.8	28.4		28.6	(1978)
1961	NM	(28.6)	28.5	28.0	27.5	26.8	27.9	28.3	28.3	28.0	27.7	27.1	26.9		28.6	(1979)
1962		27.7	28.5	(28.8)	28.4	28.3	27.3	27.3	28.0	28.4	28.6	28.5	27.6		28.8	(1980)
1963		27.0	27.9	28.4	(29.0)	28.6	27.7	26.7	26.4	27.3	28.1	28.7	28.6		29.0	(1981)
1964		27.7	27.0	27.5	28.4	(28.9)	28.8	28.2	27.7	27.2	27.9	28.5	28.6	FM	28.9	(1982)
1965	FM	(28.6)	28.2	27.6	27.1	27.5	28.2	28.4	28.3	26.9	27.5	26.9	27.5		28.6	(1983)
1966		28.3	28.8	(28.9)	28.6	28.1	27.1	27.8	28.4	28.7	(28.9)	28.4	27.4		28.9	(1984)
1967		27.0	27.7	28.2	28.4	27.9	26.9	25.6	26.4	27.4	28.3	(28.6)	28.2		28.6	(1985)
1968		26.2	26.4	27.3	(28.0)	27.9	27.6	26.8	26.3	26.5	27.8	27.9	27.7		28.0	(1986)
1969	NM	(27.9)	27.5	26.6	26.9	27.4	27.6	27.5	27.1	26.5	26.3	26.8	27.5	NM	27.9	(1987)
1970		28.2	(28.5)	28.2	27.5	26.9	26.7	27.4	27.8	27.7	27.9	27.4	27.1		28.5	(1988)

Notes. For each year the highest monthly tide within a 7-month cycle is underlined, likewise the highest annual tides (underlined in the second last column) that occur in each 4 - 5 year cycle. In each case the corresponding year of the next Saros is given in brackets (last column). Since one of the 7-month cycles is related to the full moon coincident with perigee, and the other 7-month cycle with the new moon coincident with perigee, the cycles are marked with FM or NM respectively. Highest tide of the year in brackets.

Table 28. (cont'd.)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.		Year	Next Saros cycle year
1971		28.2	28.7	(28.8)	28.4	27.6	26.3	26.2	27.1	27.9	28.5	(28.8)	28.1		28.8	(1989)
1972		27.2	27.3	28.1	28.7	(28.8)	28.2	27.4	26.5	27.5	28.2	28.6	28.5		28.8	(1990)
1973		27.3	26.6	27.2	28.0	(28.4)	(28.4)	27.4	26.8	26.5	27.3	28.1	(28.4)	FM	28.4	(1991)
1974	FM	(28.4)	28.1	27.7	27.1	27.5	27.9	28.2	28.1	28.0	27.7	27.1	28.0		28.4	(1992)
1975		27.9	28.3	28.3	28.4	27.6	26.6	27.2	27.9	28.3	(28.7)	28.6	27.9		28.7	(1993)
1976		26.8	27.5	27.5	(29.0)	28.9	28.2	27.2	27.2	28.0	28.8	28.8	28.3		29.0	(1994) 16 April
1977		27.3	26.5	27.1	28.1	28.9	(29.1)	28.4	27.1	26.4	27.7	28.2	28.6	NM	29.1	(1995) 3 June
1978		27.9	27.1	27.1	27.9	(28.4)	28.3	27.8	27.2	26.6	26.5	27.5	28.1		28.4	(1996)
1979	NM	(28.1)	27.7	27.2	27.1	27.3	27.9	(28.1)	28.0	27.7	27.7	27.5	27.1		28.1	(1997)
1980		27.2	27.8	28.1	(28.4)	28.2	27.6	26.8	27.3	27.6	28.3	28.3	27.9		28.4	(1998)
1981		27.2	26.8	27.3	27.8	(28.2)	28.1	27.5	27.0	26.7	27.6	27.8	27.9	FM	28.2	(1999)
1982	FM	(27.8)	27.4	27.0	27.3	27.7	27.5	27.3	27.3	27.0	26.9	26.8	27.4		27.8	(2000)
1983		27.6	(27.7)	27.4	27.3	27.0	26.7	27.0	27.5	27.6	27.6	27.5	27.2		27.7	(2001)
1984		27.2	27.8	28.0	28.1	27.8	26.6	26.7	27.3	27.8	(28.1)	27.9	27.1		28.1	(2002)
1985		26.4	27.0	27.4	27.9	(28.0)	27.5	26.8	26.4	27.0	27.6	27.8	27.2		28.0	(2003)
1986		27.0	26.7	27.1	(27.4)	(27.4)	27.0	26.9	26.7	26.4	26.4	26.9	26.9	NM	27.4	(2004)
1987	NM	(27.4)	27.3	26.8	26.8	26.4	26.5	26.9	27.3	27.2	27.2	27.0	26.6		27.4	(2005)
1988		27.3	(27.8)	27.6	27.7	27.3	26.4	27.0	27.4	27.7	27.7	27.3	26.5		27.8	(2006)
1989		26.5	27.3	27.7	(28.0)	27.9	27.1	26.2	26.7	27.4	27.8	27.6	27.1		28.0	(2007)
1990		26.8	26.7	27.4	(27.6)	27.4	27.0	26.8	26.6	26.2	26.9	27.2	27.2	FM	27.6	(2008)
1991	FM	(27.5)	27.4	27.3	26.7	26.9	27.1	27.4	(27.5)	27.2	27.2	26.8	27.2		27.5	(2009)
1992		27.8	(28.0)	27.8	27.6	27.0	26.6	27.4	27.7	27.9	27.8	27.2	26.5		28.0	(2010)
1993		27.2	27.8	28.0	(28.3)	27.9	27.2	26.8	27.2	27.8	28.1	27.9	27.4		28.3	(2011)
1994		27.0	27.3	28.0	(28.2)	27.9	27.4	27.0	26.6	26.8	27.5	27.9	27.9	NM	28.2	(2012) 27 April
1995		27.8	27.6	27.2	27.5	27.8	27.8	27.8	27.6	27.2	27.0	27.5	(27.9)		27.9	(2013) 13/15 June
1996	NM	(28.1)	(28.1)	27.7	27.4	27.0	27.3	27.6	27.9	27.8	27.7	27.3	27.1		28.1	(2014)
1997		27.6	(28.2)	(28.2)	28.1	27.9	27.4	27.2	27.7	27.9	28.2	28.1	27.6		28.2	(2015)

common types of tides such as those governed by diurnal inequalities. Establishment of tidal boundaries is impossible when courts assume non-existent conditions.

Tidal datums are commonly misconceived to be fixed planar levels rather than undulating time and space-dependent surfaces. Yet, except for non-astronomical factors such as storm surges, tectonic activity and postglacial sea-level rise, tidal prediction with reference to specific tide levels can be made with a high degree of confidence. In fact there is a tendency to give greater credence to the predictions and the tidal constituents on which they are based than to the observed tides. However, if the procedure is correct, the average of the predicted and observed heights should be close together. The more accurate establishment of tidal datums hinges on improved prediction, which in turn requires more reference ports, updated tidal information and improved surveying techniques. Where numerous ports exist as along the eastern Canadian seaboard and the M_2 tidal constituent is dominant, the amplitude of the M_2 tide as measured above local MSL, closely approaches MHW. Also, the exponential increase in amplitude of the semidiurnal tides in the Bay of Fundy allows MWL, HHW and the local tidal ranges to be predicted quite accurately in this home to the world's highest tides.

13. Conclusions

The hydrodynamic vigour of the Bay of Fundy rules over such geologically significant processes as erosion, sediment dynamics, and the Bay's natural resources and ecosystems. However, there is a clear need to more exactly evaluate the dynamics of the tidal regime in order to better understand the multitude of geological processes at work. Conclusions from investigations to date are summarized below.

1) Along the eastern Canadian seaboard the M_2 tidal constituent is dominant and the amplitude of the M_2 tide as measured above MSL closely approaches MHW. MSL and MHW are rising in respect to the land at an average rate of 2 to 3 mm/year.

2) As they advance toward the head of the Bay of Fundy, tidal ranges commonly exceed 15 m, and the amplitude of the dominant semidiurnal tides increases exponentially at the rate of 0.36 %/ km. This allows the local tidal range to be predicted very accurately, likewise MWL and HHW.

3) An integral part of the western North Atlantic Ocean, the Bay of Fundy tides hydrodynamically exhibit the effects of a co-oscillating tide superimposed upon the direct astronomical tide.

4) Forcing by the North Atlantic tide drives Bay of Fundy tides primarily by standing wave conditions developed through resonance; differences in the tidal range through the Bay of Fundy-Gulf of Maine-Georges Bank System are, in effect, governed by the rocking of a tremendous seiche.

5) Although dominantly semidiurnal, Fundy tides nevertheless experience marked diurnal inequalities. The overlapping of the cycles of spring and perigean tides every 206 days results in an annual progression of 1.5 months in the periods of extra high tides.

6) Extra-high tides can occur at all seasons in the Bay of Fundy, depending on the year in question. The result is considerable tidal variation throughout the year. Distinct cycles of 12.4 hours, 24.8 hours, 14.8 days, 206 days, 4.53 years, and 18.03 years are recognized.

7) Three main astronomical tide-generating factors determine the number of tides that can exceed a certain elevation during any given year: the variable distance between the Earth and the Moon; the variable positions of the Moon, Sun, and Earth relative to each other; the declination of the Moon and Sun relative to the Earth's equator.

8) Vigorous interplays between land and sea occur in northern macrotidal regimes. In Bay of Fundy estuaries, the rising sea level continually re-establishes salt marshes at higher levels despite infrequent floodings.

9) The largest tides arrive in sets of 7 months, 4.53 years and 18.03 years, and most salt marshes are built up to the level of the average tide of the 18 year cycle. Assuming local marsh level to be 1.2 m beneath the high water level of extreme high tides, an empirical High Marsh Curve allows the number of annual floodings to be determined.

10) Marigrams constructed for estuaries of rivers feeding into the Bay of Fundy show the tidal wave progressively reshaped over its course, and that its sediment-carrying and erosional capacities vary as a consequence of changing water surface gradients.

11) Changing seasons effect substantial alterations in the character of estuaries. Thus winter contributes to an already complex tidal regime, especially during the second half of the 7-month cycle. Heaviest ice conditions occur one or two months before perigean and spring tides combine to form the largest tide of the cycle. At this time, the difference in height between neap tide and spring tide is increasing, resulting in the optimal time for flooding of marshlands.

12) Changing environmental conditions in the Bay of Fundy may signal an increase in the dynamic energy of the tides. Observations indicate critical connections between tides, currents, erosion, sedimentation, and the biological community. There is a clear need to more precisely evaluate the dynamics of the tidal regime and to better understand the myriad geological processes at work.

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Appendix: Glossary of Terms

Aboiteau. Gated drainage sluice built into a dyke.

Amphidromic point. A point of zero amplitude of the observed or constituent tide.

Amphidromic system. A region surrounding an amphidromic point from which radiating cotidal lines progress through all hours of the tidal cycle.

Amplitude. Half the height or range of the wave, and the distance that the tide moves up or down from Mean Water Level.

Anomalistic cycle (monthly). Cycle in the average period (27.555 days) of the revolution of the Moon around Earth with respect to lunar perigee.

Aphelion. The point in Earth's orbit farthest from the Sun.

Apogean tide. Tide of decreased range occurring monthly when the Moon is in apogee.

Apogee. The point on the Moon's orbit that is farthest from Earth.

Argument. The angle indicated by the cosine term in an equation describing harmonic motion.

Astronomical tide (gravitational tide, equilibrium tide). The theoretical tide formed assuming that waters covering the face of the Earth instantly respond to the tide-producing forces of the Moon and Sun and form a surface of equilibrium under the action of these forces.

Barycentre. The combined centre of mass around which Earth and Moon revolve in essentially circular orbits.

CD. See "chart datum".

Celerity (of a wave). The speed or horizontal rate of advance of a wave.

Centrifugal force. Outward directed force acting on a body moving along a curved path or rotating about an axis.

Centripetal force. A centre-seeking force that tends to make rotating bodies move toward centre of rotation.

Chart datum (CD). An established elevation so low that the tides at that place will seldom if ever fall below it.

Constituents. The cosine terms in an equation describing tidal harmonic motion.

Continental shelf. Zone extending from the line of permanent immersion to the depth (average 130 m) where a steep descent occurs to great depths.

Coriolis effect. Also known as Coriolis force. An apparent force acting on a body in motion, due to rotation of the Earth causing deflection to the right in northern hemisphere and to the left in southern hemisphere.

Cotidal lines. Lines on a map giving the location of the tide's crest at stated time intervals.

Crest of a wave. Highest part of a propagating wave.

Current. A horizontal movement of water.

Declination. The angular distance of the Moon or Sun above or below the celestial equator.

Diurnal. Daily tides; having a period or cycle of approximately one tidal day.

Diurnal inequality. The difference in height between the two High Waters or the two Low Waters of each tidal day.

Drumlin. A streamlined hill of compact glacial fill formed by a glacier.

Dynamic tidal theory. Model of tides that takes into account the effects of finite ocean depth, basin resonances and the presence of continents.

Ecliptic. The plane of the centre of the Earth-Moon system as it orbits around the Sun; the intersection of the plane of Earth's orbit with the celestial sphere.

Equal High Water (EHW). Two daily high tides of equal height.

Equal Low Water (EHW). Two daily low tides of equal height.

Equilibrium theory. See "astronomical tide".

Equilibrium tide. Hypothetical tide due to the tide-producing forces under the equilibrium theory; also known as the gravitational tide.

Equinox. Times of the year when the Sun stands directly above the equator so that day and night are of equal length around the world (about 21 March and 22–23 September).

Estuary. A coastal embayment into which fresh river water enters at its head and mixes with the relatively saline ocean water.

Eustatic. Pertaining to global changes of sea level that affected all oceans as a result of absolute changes in the quantity of sea water.

Evectional (monthly) cycle. The time required for the revolution of Moon around Earth, depending upon the variation of the eccentricity of its orbit.

Exponential (growth). A variable with a constant growth rate is said to increase exponentially.

Forced wave. A wave generated and maintained by a continuous force.

Free wave. A wave that continues to exist after the generating force has ceased acting.

Frequency of wave. The number of cycles that pass a location during a unit of time.

Gravity wave. A wave from which the restoring force is gravity.

Harmonic analysis. The mathematical process by which the observed tide or tidal current at any location is separated into harmonic constituents.

Head. The difference in water level at either end of a strait, channel, etc.

Height (range) of a wave. Vertical distance between wave crest and the adjacent wave troughs.

Higher High Water (HHW). The higher of two daily High Waters.

Higher High Water, large tide (HHWLT). Average of the highest high waters, one from each of 19 years of predictions.

Higher High Water, mean tide (HHWMT). Average of all the high waters from 19 years of predictions.

Higher Low Water (HLW). The higher of two daily Low Waters.

High Water (HW). Maximum height reached by a rising tide as a result of periodic tidal forces and the effects of meteorological, hydrologic and/or oceanographic conditions.

Holocene. The latest epoch of the Cenozoic era, from the end of the Pleistocene epoch to the present time. In northern latitudes, it generally equates with the postglacial interval.

Ice factories. Open water consisting of an unconsolidated mixture of needle-like ice crystals and sediment-laden waters.

Ice walls. Vertical walls of ice up to 5 m high formed in a rectangular estuarine channel under winter conditions.

Intertidal zone. The zone between mean higher high water and mean lower low water lines.

Isostatic compensation. Adjustment of crust of the Earth to maintain equilibrium among units of varying mass and density.

Julian calendar. Introduced by Julius Caesar 45 B.C.E., this calendar provided that the common year should consist of 365 days, and that every fourth year, now known as leap year, should contain 366 days, making the average length of the year 365.25 days. It differs from the modern (Gregorian) calendar in which the calendar century years not divisible by 400 are common years.

K_1. Luni solar diurnal constituent; with O_1 it expresses the effect of the Moon's declination.

K_2. Luni solar semidiurnal constituent; it modulates amplitude and frequency of M_2 and S_2 for the declinational effect of the Moon and Sun, respectively.

Knot. Speed unit of one nautical mile (1852 metres) per hour.

L_2. Smaller lunar elliptic semidiurnal constituent; with N_2 it modulates the amplitude and frequency of M_2 for the effect of variation in the Moon's orbital speed due to its elliptical orbit.

Lag (deposit). Larger sedimentary particles remaining after smaller particles are washed away.

Latitude. Angular distance between point on the Earth and the equator measured north or south from the equator along a longitudinal meridian.

Longitude. Angular distance along the equator east and west of Greenwich measured in degrees or hours, the hour being taken as 15° of longitude.

Lower High Water (LHW). The lower of two daily High Waters.

Lower Low Water (LLW). The lower of two daily Low Waters, or a single Low Water.

Lower Low Water, large tide (LLWLT). Average of lowest low waters, one from each of 19 years of predictions.

Lower Low Water, mean tide (LLWMT). Average of all the lower low waters from 19 years of predictions.

Lowest Normal Tide (LNT). Currently synonymous with LLWLT; it is also called chart datum (CD).

Low Water (LW). Lowest height of the tide in daily cycle.

Lunar day. The time of Earth's rotation with respect to the Moon; mean lunar day = 24.84 solar hours.

Lunar month (synodical month). A period of 29 ½ days in which the Moon passes through four phases: new moon, first quarter, full moon, and last quarter.

M_1. Smaller lunar elliptic diurnal constituent; it helps to modulate the amplitude of the declinational K_1 for effect of the Moon's elliptical orbit.

M_2. Principal lunar semidiurnal constituent; it represents the rotation of Earth with respect to the Moon.

Macrotidal. Tidal system in which the tidal range exceeds 4 m.

Marigram (tidal curve). A graphical record of the rise and fall of the tide.

Mean Higher High Water (MHHW). The average of the Higher High Water height on all tidal days observed during a tidal datum epoch.

Mean High Water mark (MHW). The level reached by the M_2 amplitude above MSL; in Canada, usually taken as equivalent to "ordinary" high water (OHW).

Mean Low Water (MLW). The average of the Lower Low Water height of all tidal days during the tidal datum epoch.

Mean Lower Low Water (MLLW). The average of the Lower Low Water height on all tidal days observed during a tidal datum epoch.

Mean Sea Level (MSL). The level that oceanic water would assume if no tidal or atmospheric influences are acting upon it.

Mean Water Level (MWL). Average of all hourly water levels with respect to chart datum observed over the available period of record.

Meridian. Circle of longitude passing through the poles and any given point on Earth's surface.

Meterological tides. Tidal constituents having their origin in daily or seasonal variations in weather conditions which may occur with some degree of periodicity.

MHW. See Mean High Water mark.

Mixed tide. Tide having a conspicuous diurnal inequality in the Higher High and Lower High Waters and/or Higher Low and Lower Low Waters.

Moraine. Hill or ridge of sediment deposited by glaciers; geomorphologic name for a land form composed mainly of till deposited by either an extant or extinct glacier.

MSL. See Mean Sea Level.

MWL. See Mean Water Level.

N_2. Longer lunar elliptic semidiurnal constituent; with L_2 it modulates the amplitude and frequency of M_2 for the effect of variation in the Moon's orbital speed.

Neap tide. Tide occurring near the first and last quarter of the moon, when the range of the tide is least.

Nodical month. Average period (27.212 days) of the revolution of the Moon around Earth relative to its passing through the ecliptic.

O_1. Lunar diurnal constituent; with K_1 it expresses the effect of Moon's declination; and with P_1 it expresses the effect of the Sun's declination.

Ordinary High Water (OHW). In Canada, a level in surveying practice taken as equivalent to Mean High Water.

Outwash (glacial). Stratified detritus washed out from a glacier by melt water streams and deposited beyond the terminal moraine or margin of active glacier.

Overpressure. Excessive pressure.

Overtides. Analogous to overtones in music, and considered as higher harmonics of the fundamental tides.

P_1. Solar diurnal constituent; with K_1 it expresses the effect of the Sun's declination.

Perigean tide. A spring tide occurring monthly when the Moon is at or near perigee of its orbit.

Perigee. The point on the Moon's orbit that is nearest Earth.

Perihelion. The point in Earth's orbit nearest to the Sun.

Period. Interval required for the completion of a recurring event or any specific duration of time.

Phase lag. Angular retardation of a maximum of a constituent of the observed tide behind the corresponding maximum of the same constituent of the equilibrium tide.

Prime meridian. Meridian of longitude passing through the original site of the Royal Observatory, Greenwich, England.

Progressive wave. A wave of moving energy in which the wave form moves in one direction along the surface of the medium.

Q_1. Larger lunar elliptic diurnal constituent; with (M_1), it modulates the amplitude and frequency of the declinational effects of the Moon and the Sun.

Refraction. The bending of the wave crest due to changing depths.

Resonance. Tidal motions on Earth are forced motions resulting in large scale oscillations analogous to a swinging bob of a pendulum. If the energy imparted exceeds the limits of true oscillation, a state of resonance is said to occur. If the dimensions of a gulf or sea allow for a period of free oscillation equal to that maintained in the ocean, resonance may occur.

S_2. Principal solar semidiurnal constituent; it represents this rotation of the Earth with respect to the Sun.

Salt marsh. A low-lying flat area of vegetated marine soils that is periodically inundated by saltwater.

Saros. The 18.03 yr cycle in which Moon, Sun and Earth return to almost identical relative positions; a cycle in which solar and lunar eclipses repeat themselves under approximately the same conditions.

Seiche. A standing wave oscillation of an enclosed or partly enclosed body of water that continues to oscillate after the generating force ceases.

Semidiurnal. Twice daily tides; having a period/cycle of approximately one-half of a tidal day.

Set up (of the wind). Flow of wind such that the water is driven toward the shore line.

Sidereal day. The time of Earth's rotation with respect to the vernal equinox.

Sidereal month. Average period (27.322 mean solar days) of the revolution of Moon around Earth relative to a fixed star.

Sidereal time. Time usually defined as the hour angle of the vernal equinox.

Sidereal year. Average period of the revolution of Earth around the Sun with respect to a fixed star.

Slack water. For a perfect progressive tidal wave, this occurs midway between high and low water.

Solar day. The period of Earth's rotation with respect to the Sun.

Solstice. Times of the year when the Sun stands above 23.5°N or 23.5°S latitude (about 22 December and 22 June).

Spring tide. Tide occurring near new and full moon, when the range of the tide is greatest.

Standard time. With few exceptions, standard time is based upon some meridian which differs by a multiple of 15° from the Greenwich meridian.

Standing wave. Type of wave in which the water surface oscillates vertically without progression between fixed nodes.

Storm surge. The local change in the elevation of the ocean along the shore due to a storm. It is measured by subtracting the astronomic tidal elevation from the total elevation.

Storm tide (storm surge). A sudden abnormal rise (positive) or fall (negative) of sea level due to change in atmospheric conditions along a coast. The sum of the storm surge and astronomic tide.

Synodical month. The average period of the revolution of the Moon around Earth relative to the Sun's position (29.531 days).

Thalweg. The median line of a stream or channel.

Tidal bore. A tidal wave that propagates up a relatively shallow and sloping estuary or river channel with a steep wave front, the leading edge rises abruptly, often with continuous breaking and commonly followed by several large undulations.

Tidal constituent (partial tide). A cosine curve representing the influence or characteristic of the local tide.

Tidal creek. Is a creek formed by tidal water that moves onto a tidal marsh during the Higher High Waters, discharging with the turn of the tide.

Tidal curve. See "marigram".

Tidal day. The time interval between two successive passes of the Moon over a meridian (about 24 hours, 50 minutes).

Tidal estuary. The mouth of a tidal river where the tidal flow regime shapes the channel bed.

Tidal prism. The top part of the estuary between the Low Water and the High Water levels.

Tidal range. Total vertical distance between High Water and Low Water. Note. In Canadian Tide Tables, the range at a given location is the distance between Higher High Water and Lower Low Water.

Tidal river. The stretch of a fresh water river where the dominant factor shaping the channel is fresh water.

Tide. The periodic rise and fall of a body of water resulting from gravitational interaction between Sun, Moon and Earth.

Tide producing force. That part of the gravitational attraction of the Moon and Sun which is effective in producing the tides on Earth.

Tide wave (tidal wave). Long period gravity wave originating in the tide-producing force and manifest in tidal ebb and flow.

Tiding (warping). Transformation of salt marsh into grasslands by use of canals to focus tidal inundations of sediment-charged seawater.

Tractive force. The horizontal component of a tide-producing force vector.

Tropical monthly cycle. The average period (about 27.322 days) of the evolution of the Moon around Earth relative to the vernal equinox.

Trough. The lowest point in a propagating wave.

Tsunami. A seismic sea wave; in literal translation from Japanese meaning “a long wave in harbour”.

Universal time. Same as Greenwich Mean Time.

Vernal equinox. See “equinox”.

Wave height. The vertical distance between crest and trough.

Wave length. Horizontal distance between two successive wave crests or troughs.

Wave train. A series of waves from the same direction; also known as a wave set.

Z_0. Symbol recommended by the International Hydrographic Organization to represent the elevation of mean sea level above chart datum.