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The Tidal Power Potential of Ungava Bay and its Possible Exploitation in Conjunction with the Local Hydroelectric Resources

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Foreword

The material presented in this manuscript report complements the information contained in a paper entitled: "The Power Potential of Ungava Bay and its Hinterland" to be published in the magazine Water Power. Two sections here, 4.4 and 6., are extracted verbatim from that paper.

Gabriel Godin.

G. Godin
Marine Sciences Directorate

January 4, 1973
Ottawa.

Contents

1. Introduction

The tidal range at the entrance of the Koksoak River in Ungava Bay may reach 12.6 m, while inside Leaf Basin a little further to the northwest, it may get as high as 13.4 m. The range at Saint John, N.B. half-way up the Bay of Fundy is about 10 m. Considering that the volume of water contained in Ungava Bay is five times as large as in the Bay of Fundy, one realizes that much more tidal energy is present in Ungava Bay.

Only 240 MW (the Rance Project) of the 64,000 MW of tidal power available on this earth (Hubbert, 1971) have been exploited. It is evident that we should attempt to extract more of this power whenever it is of easy access. Putting aside the economical question for the moment, the remaining major stumbling blocks to the realization of a tidal power plant are the intermittency of its output and its rather extreme variability over an interval of 15 days (between neap and spring tide). Elaborate schemes have been derived that would supply almost steady power from the tide, but they have never gone beyond the draughting table because they are clumsy and wasteful. Even pumped storage would lead to almost insuperable difficulties in a subarctic climate where the temperature hovers around -30°C for a good part of the year and may plunge as low as -50°C

Bernshtein (1965) supplied a simple answer to the problem of the intermittency of tidal power: he proposed that with each tidal plant there be associated one or more hydro plants of equal or larger capacity. In this way, it would be possible to let the tidal plant supply all of its energy while the hydro plant would increase or decrease its output, depending on the demand. In this way, the necessity of pumped storage is eliminated, maximum use is made of the tidal energy, the potential energy of the river water is exploited to nearly maximum efficiency, the base load and peak demand are met either by the tidal plant or by the hydro plant or by both depending on the astronomical conjunctures (section 3.4). Since tidal power, averaged over a month or a year, is nearly constant and is accurately predictable, the use of the water stored in the river may be planned on a monthly or yearly schedule. Such a scheme of exploitation has already been proposed for the Passamaquoddy project, which unfortunately was not carried out in spite of its sound economics (Anon., 1961).

A look at the map of Ungava Bay and its hinterland (Figure 1) does indicate the presence of rivers carrying a considerable amount of hydraulic energy: the Payne, the Leaf, the Koksoak-Larch-Kaniapiskau system, the Whale and the George Rivers all have their sources in the interior highlands and drop from heights of 220 to 740 m. Their discharge is far from negligible and the Koksoak in particular has a mean discharge of 2,420 m^3/sec (Anon., 1971). Together, they have a realistic power potential of some 12,000 MW (see Table 4) which sooner or later will become of interest to the centers of consumption of power further south.

In Ungava Bay proper the following basins could be tapped for tidal power: Payne Bay, Ikattok Bay, Leaf Basin, the Koksoak River estuary, the False River Basin, the George

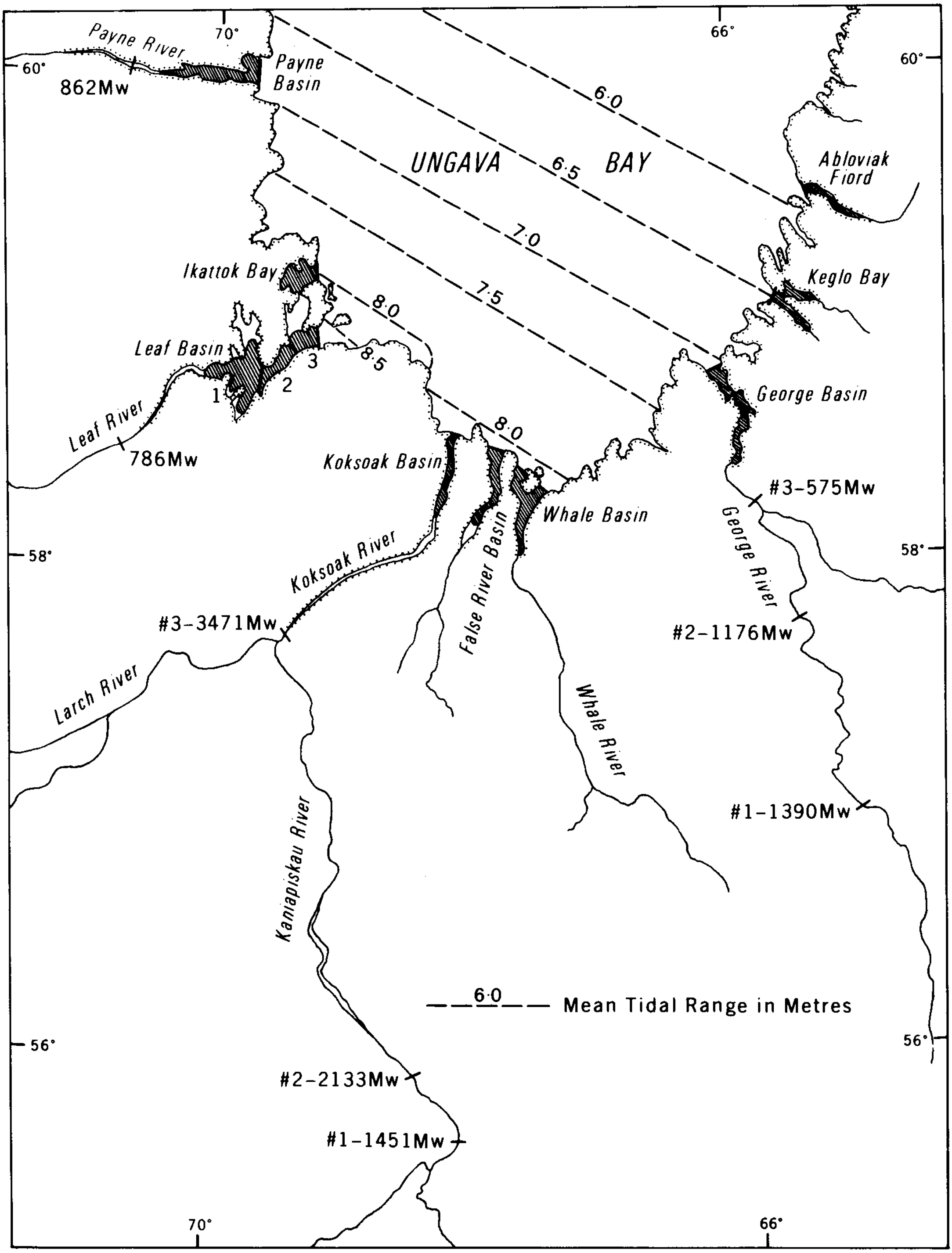

Fig. 1 Ungava Bay and its hinterland. Mean tidal range in meters; basins which could be impounded for the generation of tidal power; major rivers and suitable sites for the construction of dams with the estimated gross power yield in MW.

River estuary, the Whale River estuary, Keglo Bay and Abloviak Fiord. Their combined mean power output (which unfortunately does not mean very much since tidal power comes in short-lived bursts) would be of the order of 5,400 MW. Leaf Basin would be in a position to supply about 3,000 MW of mean power with mean peaks of 5,500 MW and occasional bursts of 10,500 MW. Such figures are impressive although a closer scrutiny of the tidal basins mentioned might eliminate some of them. However, Leaf Basin appears as an ideal site to exploit, from the point of view of shelter and ease of construction. The output of the more suitable sites could certainly be combined with those of the rivers, harnessed according to the Bernshtein scheme, to make the best possible use and the most rational exploitation of the hydraulic energy present in Ungava Bay proper and in the rivers of its hinterland.

With this in mind, we will review the principles underlying the exploitation of tidal energy (section 1.1) and we will estimate the power potential of the bays and estuaries on the periphery of Ungava Bay (section 1.3) as well as the hydro potential of the rivers of the Ungava hinterland (section 2). With these data it will be possible to study the exploitation of a combination of tidal plants and hydro plants (section 3.4).

The economics of such an undertaking are beyond our competence. They do not seem bright at the moment because of the very large distance between the Ungava sites and the centers of consumption. For instance, the plant at Leaf Basin would be 1,500 km away from Montreal. The economic prospects might improve drastically with the development of new techniques of transmission such as the transformation of electrical energy into microwaves at the plant site and their reflection by satellites to reception areas close to the centres of consumption, with little loss of energy (Summers, 1971). The establishment of sheltered cities and local industries in the Ungava area is also conceivable.

2. Tidal power

2.1 The features of tidal energy

If the range of tide is R meters and the area of the basin affected by it is A meters^2, the energy necessary to raise the centre of gravity of RA m^3 of water $\frac{1}{2}$R m above the low water level amounts to

$$E = \tfrac{1}{2}\rho g A R^2 \text{ kilojoules}^{+} \tag{1}$$

ρ = density of the water in tons/m^3 and g = acceleration due to gravity (9.8 m/sec^2).

As an example, the mean range of the tide in the Bay of Fundy is about 7 m while the area of the bay is approximately 9.32 x 10^9 m^2, so that equation 1 gives

$$E = 2.24 \times 10^{12} \text{ kj}$$

[+] Engineers usually compute energy by the kilowatt-hour which is equivalent to 3,600 kilojoules

This energy, if expended steadily over the time needed to raise the mass of water (6.2 hrs), would yield power at the rate of

$$P = 10^8 \text{ kilowatts} = 10^5 \text{ megawatts}$$

This could satisfy the power requirement of all eastern North America till 1990, but we should not be too impressed by the figure for while these 10^5 MW may all be in the Bay of Fundy, they do not work for us, they simply lift the water by 7 m.

The first drawback of tidal power is its diffuseness. The 10^5 MW of the Bay of Fundy are distributed over an area of 9.32×10^9 m^2: the concentration of tidal energy is, therefore, 0.0107 kw/m^2. In contrast, a very modest waterfall tumbling down 15 m with a discharge of 150 m^3/sec going through a pair of turbines of total throat area of 100 m^2 would have a power density of 221 kw/m^2; a power concentration 20,000 times more intense than in the Bay of Fundy. As a final contrast, the mean solar radiation falling on Moosonee (latitude 52°N and certainly not highly favored by the sun) amounts to 25 langleys/hr or 0.29 kw/m^2, which is still thirty times as large as the average tidal power spread over the bottom of the Bay of Fundy (Wilson, 1971).

The basic prerequisite to the successful extraction of tidal power is, therefore, its concentration into exploitable density. Tidal energy is distributed over the whole of the water mass, but is transmitted horizontally through successive vertical sections. For instance, the whole of the tidal energy present in a bay has to enter and exit through its mouth and the power going through will be distributed eventually over the whole water mass. The energy entering and leaving the bay over a complete tidal cycle will be, according to equation 1

$$E_{total} = \rho g A R^2 \text{ kj} \qquad (2)$$

expended over about 12.4 hrs.

Some of this energy may be captured by erecting a barrage at the mouth of the basin and installing turbines inside it. The establishment of a head on either side of the barrage will activate the turbines and if a very large quantity of water is allowed to run through them, a respectable amount of energy could be generated during the tidal cycle. This scheme can be described by the change of levels inside and outside the tidal basin (Figure 2). The smooth curve represents the tide in the sea outside the basin, while the broken line represents the level of the basin. It may be seen that the range inside the basin is less than that of the tide outside; this loss of range is unavoidable because of the presence of the turbines and the reduced rates of emptying and filling of the basin. These rates depend on the capacity of the turbines and the auxiliary sluices. Too small a capacity would reduce the working range R' while a large capacity would require the installation of a large number of turbines with a low rate of utilization. We note that this scheme of exploitation also implies: a) an intermittent generation of power and b) a net yield of energy definitely smaller than the value quoted in equation 2.

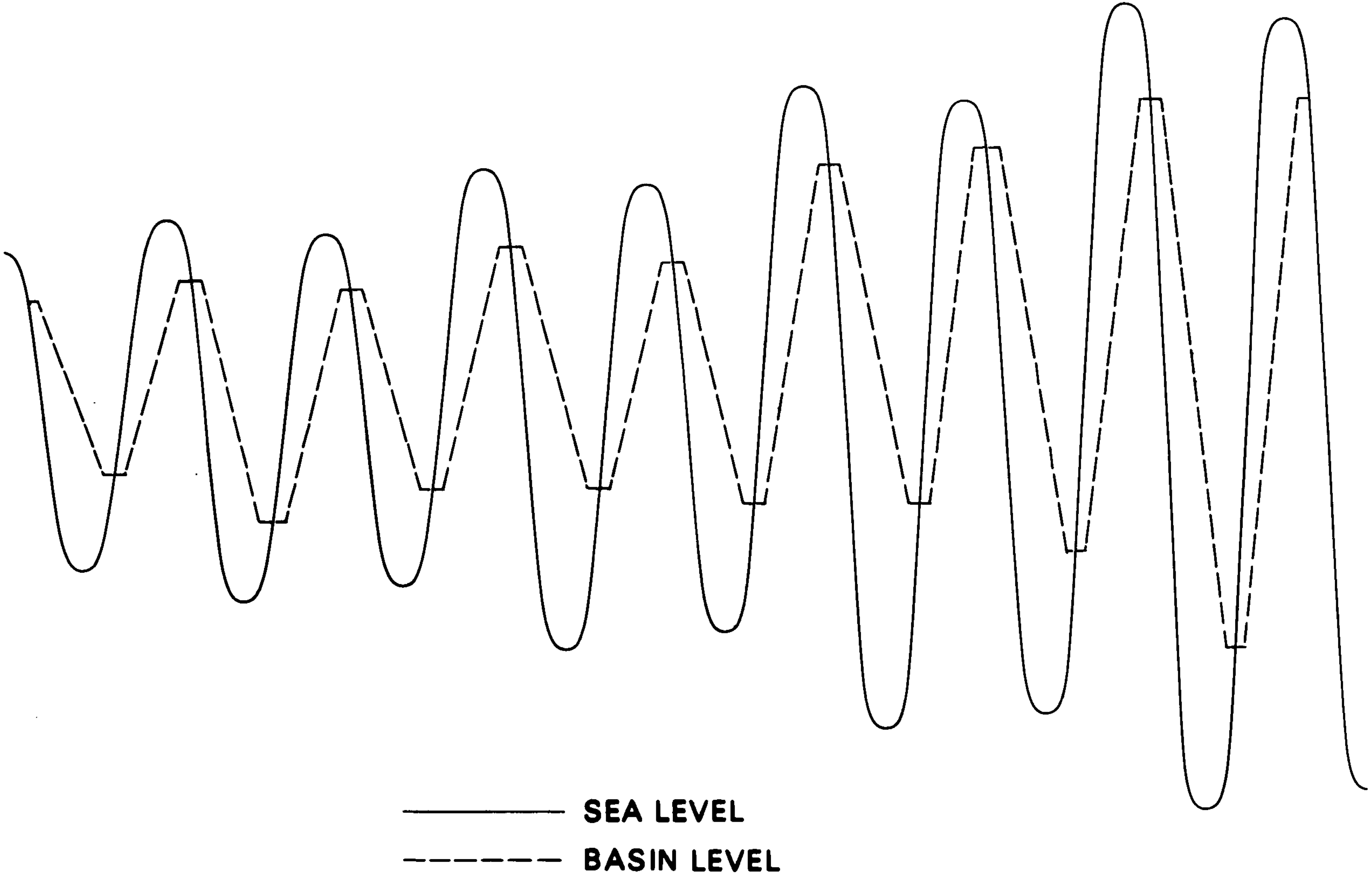

Fig. 2 Level variations inside the tidal basin contrasted with the sea level variations on the ocean side of the dyke (schematic).

Figure 2 also attempts to indicate some additional characteristics of tides which influence their exploitation, for example: a) where tides do have a large range, they are caused predominantly by the influence of the moon and, therefore have periods of about 12 hrs 25 min (half a lunar day). Relative to clocks set according to the sun, as most clocks are, they seem to retard by 50 min a solar day, b) their range exhibits daily and semimonthly oscillations. A larger range is followed by a smaller one and the ranges reach maximum values (spring tide) and minimum values (neap tide) over an interval of fifteen days.

The diurnal inequality is not too great in areas where the tide is large because the semidiurnal constituents are much larger than the diurnal ones, but the fortnightly variations are most serious. For instance, the spring range is 11.4 m in Leaf Basin while the neap range is 5.9 m. Since the tidal energy varies with the square of the range according to equation 2, the ratio of energy input into Leaf Basin between spring and neap tide is nearly 4:1. The energy production at the site would exhibit variations of the same magnitude. In order to exploit fully the energy available, we would have to install a large number of turbines whose rate of utilization would be fairly low and finally, c) in contrast to rivers, tides are largely uncontrollable; they come at their own time with the range of their choice. Tide modification is theoretically feasible but really not possible in practice.

These very characteristics of tides have been resolutely opposed by most engineers who, in many other domains, have succeeded in forcing nature to do exactly what they wanted, although they just cannot achieve the same mastery of tides. Even in a very recent investigation (Anon., 1969), a desperate search was made for dependable peak power from a tidal plant, something which a tidal plant just cannot provide on its own. The result of all those misguided efforts, is that of all the tidal plants proposed, only the Rance and Kislaya Projects have been actually constructed. They both represent an exceedingly small scale effort to tap a form of energy which is quite abundant in some parts of the world.

Both the Rance and Kislaya projects are of the single basin double effect type which yields the most energy at the lowest cost (Bernshtein, 1965 Table 4-1, p. 38-39). Any other scheme of exploitation will yield less energy (Davey, 1923 p.58). We will contemplate only this type of exploitation throughout our investigations. Figure 3 shows a schematic representation of the arrangement. A barrage is built across the mouth of the basin in which the turbines and sluices are housed; the turbines operate during the filling and emptying of the basin. The mouth of the basin should be of such a width that it can house all the necessary turbines. Large capacity turbines will require less width; however, contemporary technology does not allow turbines with a runner much over 12 m in diameter, although it would be theoretically desirable in the case of a tidal plant to have turbines with even larger runners. Figure 4 shows schematically the relation between the change in basin level and the power generation. The power generated on emptying is larger in general

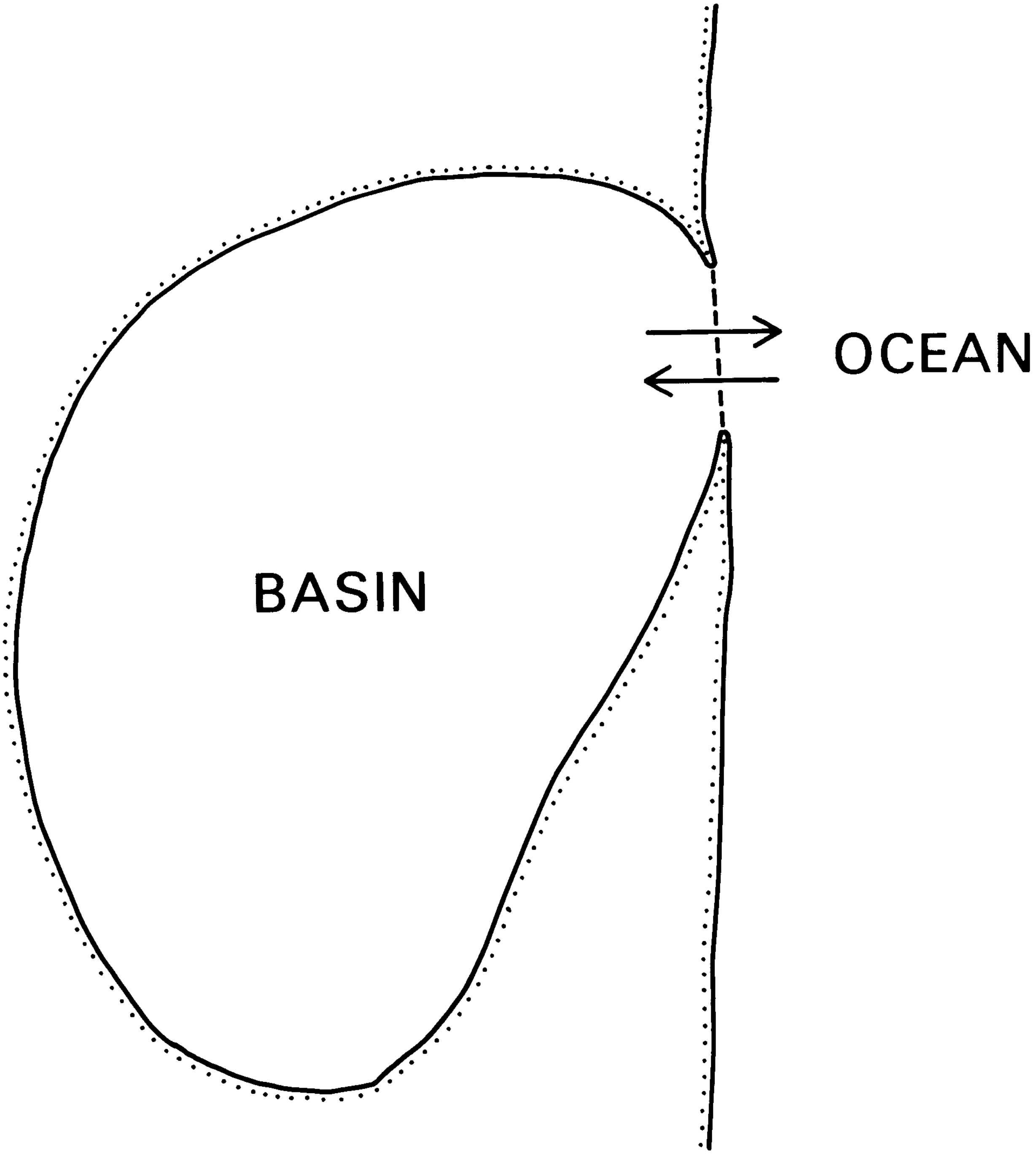

Fig. 3 Single basin double effect scheme for the exploitation of tidal power. The basin is cut off the ocean by a dam. Inside the dam, turbines generate power exploiting the head difference between the basin and the ocean during the ebb or flood. Some auxiliary sluices may also be installed within the dam to accelerate the emptying and filling of the basin at the end of the cycles.

than during the filling because the sides of a basin are seldom vertical so that the storage capacity is less at low water than at high water.

The output of a power plant which comes as relatively short-lived bursts of power is definitely not acceptable for human consumption; we must have the energy when we want it at a rate which meets the instantaneous demand. A tidal plant of the type contemplated cannot operate on its own unless its output is a very small fraction of the total power requirement as is the case for the Rance. Otherwise it has to be exploited in conjunction with other sources of energy which could compensate for the inequalities of the tidal power output. In the case of Ungava Bay, the obvious choice of compensating plants would be those hydro plants which could be built on the rivers emptying into the bay.

2.2 The tide in Ungava Bay

The tide has been observed only at a few isolated stations on the periphery of Ungava Bay over short intervals of 15 or 29 days. One of the stations was installed in Leaf Basin and could record only the local tide and not the main tide typical of Ungava Bay. We show the location of the stations in Figure 5 and in Table 1 we list the values of the semidiurnal and diurnal constituents, moving clockwise. The coverage leaves a huge blank in the eastern section.

The observations are not extensive enough to allow the empirical evaluation of the mean, maximum and minimum ranges, quantities which are of fundamental importance to the design of a tidal plant. To fill this void, we take M_2 as giving the mean amplitude, M_2+S_2 and M_2-S_2 for the spring and neap amplitudes and $M_2+S_2+N_2$ and $M_2-S_2-N_2$ for the largest and smallest amplitudes which will be encountered on the average. Such estimates are not accurate and tend to underestimate the actual ranges. The estimated ranges are listed in Table 2.

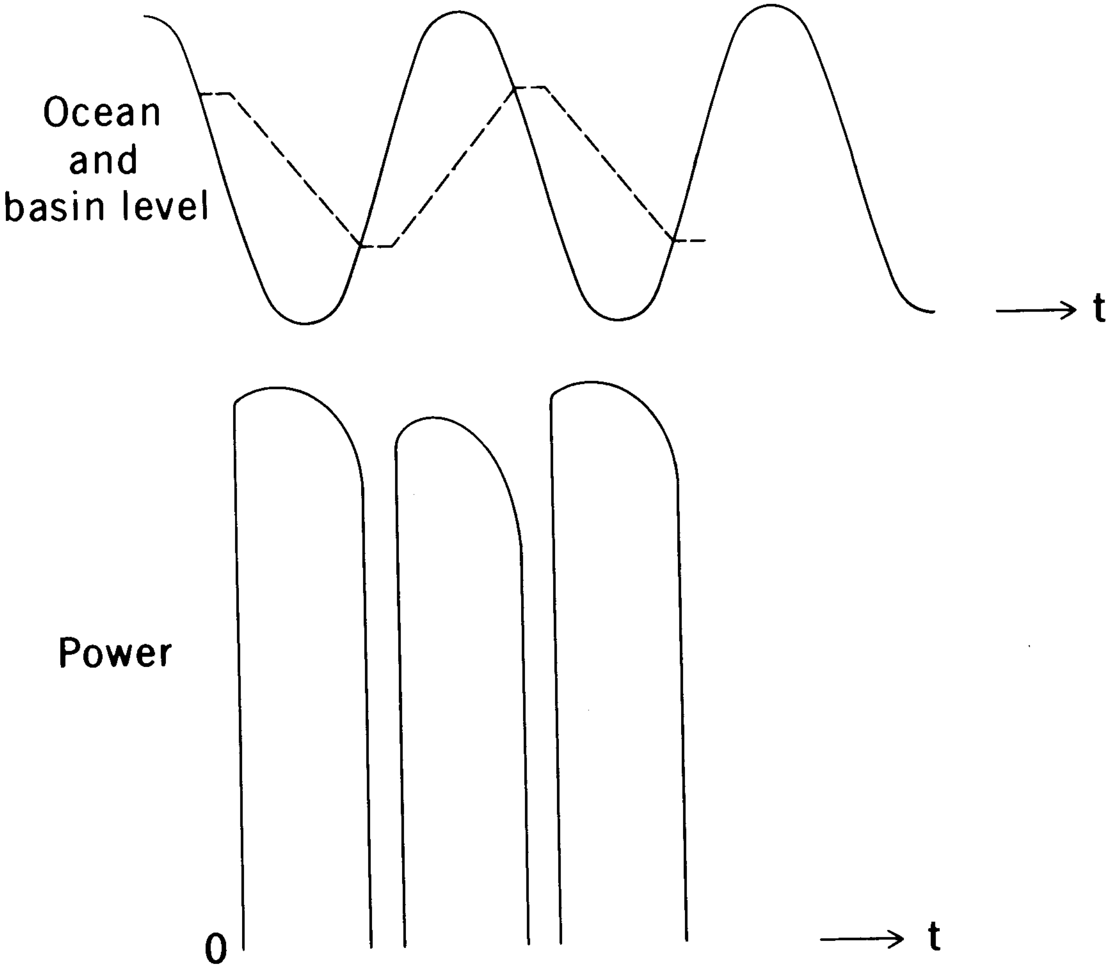

Fig. 4 Power production in relation to the difference in level between the tidal basin and ocean. The dashed line is the basin level while the continuous line is the sea level. The power comes out in intermittent bursts with less energy being produced during the filling of the basin than during the emptying.

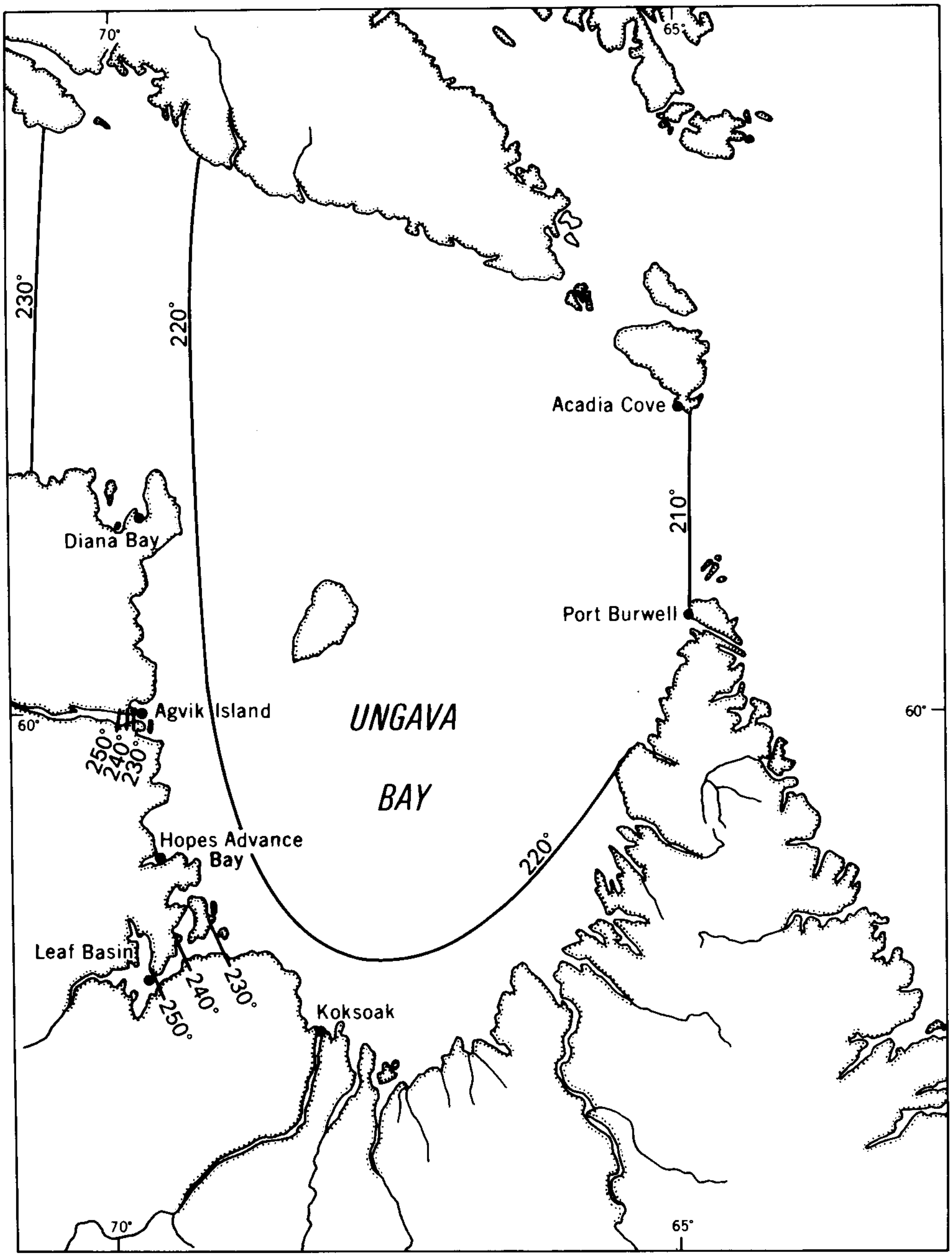

Fig. 5 Cotidal lines of the M2 tide in Ungava Bay. The tide appears as reaching the whole shore at nearly the same time. No information whatsoever is available to determine the timing of the tide between the Meta Incognita Peninsula and Resolution Island: as a consequence the space has been left blank. The dots denote the sites of the temporary gauge stations.

Table 1 The major constituents of the tide in Ungava Bay

Greenwich phase lags referred to time zone $^{+}5$ (Eastern Standard Time)

Station	Semidiurnals						Diurnals			
	M_2		S_2		N_2		K_1		O_1	
	m	deg	m	deg	m	deg	m	deg	m	deg
Acadia Cove (Resolution)	2.15	211	0.89	246	0.43	188	0.13	115	0.15	84
Port Burwell	2.15	209	0.65	258	0.42	177	0.12	90	0.09	45
Koksoak River Entrance	4.09	229	1.36	282	0.76	196	0.16	91	0.13	53
Leaf Basin	4.33	251	1.37	314	0.92	223	0.19	113	0.07	85
Hopes Advance Bay	3.88	225	1.25	288	0.83	188	0.21	97	0.10	45
Agvik Island (Payne Bay)	3.49	225	1.17	275	0.65	199	0.18	110	0.11	27
Diana Bay	2.93	224	0.99	276	0.59	198	0.16	88	0.09	47

Table 2 Approximate values of the largest, spring, mean, neap and smallest ranges at the stations listed in Table 1

Station	largest $2(M_2+S_2+N_2)$ m	spring $2(M_2+S_2)$ m	mean $2M_2$ m	neap $2(M_2-S_2)$ m	smallest $2(M_2-S_2-N_2)$ m
Acadia Cove	6.94	6.08	4.30	2.52	1.66
Port Burwell	6.44	5.60	4.30	3.00	2.16
Koksoak River	12.42	10.90	8.18	5.46	3.94
Leaf Basin	13.24	11.40	8.66	5.92	4.08
Hopes Advance Bay	11.92	10.26	7.76	5.26	3.60
Agvik Island	10.62	9.32	6.98	4.64	3.34
Diana Bay	9.02	7.84	5.86	3.88	2.70

Tables 1 and 2 indicate that the ranges reach their maximum in the area which stretches from the mouth of the Koksoak River to Payne Bay; we have indicated in Figure 1 our interpretation of the lines of equal ranges in the bay. Although the eastern portion is not covered, we assume that M_2 has values intermediate between 2.15 and 4.09 m. With respect to phase, M_2 is nearly simultaneous between the Koksoak River and Diana Bay; we interpret the larger phase in Leaf Basin as an effect of the remoteness of the gauge from the main body of the bay. We have drawn in Figure 5 our interpretation of the cotidal lines of M_2; they are speculative to a degree. We assume, on the basis of the observations at Acadia Cove and Port Burwell, that M_2 enters Hudson Strait with a uniform phase and from the other stations, that M_2 is nearly simultaneous around the periphery of Ungava Bay. If this is so, the tide in Ungava Bay behaves very much like a standing wave. When it comes to the amplitude, we assume it to increase steadily from 2 m between the islands of Resolution and Killinek to 4 m towards Leaf Basin. The other semidiurnal constituents S_2 and N_2 behave in the same way as M_2 but more irregularly, probably because of the shortcomings of the analysis.

The diurnal constituents K_1 and O_1 do not exhibit the same amplifications towards Leaf Basin; their combined amplitude remains less than 30 cm throughout the bay. Since they are mainly responsible for the diurnal inequality we must expect that the diurnal inequality in the tidal basins of interest will almost never exceed 30 cm and will be much less than that on the average. It is, therefore, of minor importance.

2.3 The tidal power potential of Ungava Bay

In Figure 1 we have shaded the basins around Ungava Bay which could be impounded and exploited for tidal power. The energy available at each site depends, according to equation 2, on the area A of the basin and on the square of the range R. This implies that the same investment would yield greater returns in the vicinity of the Koksoak River and Leaf Basin because of the larger ranges there. On the other hand a closer look at the bottom geology, local climate and wave exposure might perhaps favor some other site in spite of a smaller yield of energy. Since we know next to nothing about the bottom topography, geological structure and exposure of these basins, it is necessary in this preliminary investigation to assess them exclusively on their energy yield.

Even at that, formula 2 is only a very rough first approximation to the actual potential of the basin; dynamical factors come in which it does not take into account. The existence of contractions such as the Narrows in the Koksoak estuary will impede the free flow of water during the filling and emptying operations, thereby reducing the effective range which can be maintained, and complicating the exploitation by introducing extra delays. Also, each of the basins considered has its own natural modes of oscillations which may be excited during the operations; these oscillations may be helpful or catastrophic depending on their phase and amplitude. In any case, they will have to be closely studied when a more exacting study of the site is made. We also tend to use as a representative range inside the basin, the range at the mouth. In reality, the tidal range may increase or decrease inside the basin depending on its configuration and the influence of friction. There is some indication that the range increases inside Leaf Basin although this will have to be checked. At Payne Bay, the observations on three islands, Agvik, Basking and Pikiyulik, seem to indicate that the range decreases quite rapidly inside. We have no information whatsoever about the others.

The area A is not a constant and varies with the stage of the tide; the use of a mean value cannot be too wrong provided the variation is approximately linear. When it comes to the values of energy given by equation 2, we assume that we can recover at most 30% of it with the tidal plant. For example, the Rance has a planned efficiency of 29%; an efficiency which was not too difficult to achieve on account of the relatively small size of the project and the rather reasonable shape of the estuary.

We can delineate more than one possible scheme in Leaf Basin and these have been denoted by 1, 2 and 3 in Figure 1. We do not have as yet sufficient information to favor one over the others. The only difference between them is that at first sight, they would yield increasing amounts of energy. The innermost, scheme 1, might turn out to be the most favourable after closer study because of its beautifully sheltered position and safety from ice pressure, although it yields the least energy. Project 2 would supply a third of the potential output of Minas Basin in the Bay of Fundy and from a practical point of view, its construction would be very much easier. Payne Basin and Ikattok Bay also appear as favourable sites although they would yield less energy than any scheme in Leaf Basin. Nevertheless, their individual output would still be over five times as large as that of the Rance; we are then considering ranges of tidal energy which have not yet been tackled.

It may also be found that once the construction of one tidal plant has been decided on, the actual capital investment would be such that it would be worthwhile exploiting all the other favourable sites using the experience gained and the manpower and equipment available. In this case, the estuaries or basins of the False River, Whale River, George River, Keglo Bay and Abloviak Fiord could be included in the scheme even though their individual outputs are not too impressive. We have summarized in Table 3 some tidal power information about the sites shaded in Figure 1. The power and energy figures assume an efficiency of the plant of 30%. The annual energy output E_y may be considered as making physical sense since approximately that many kw-hr could be generated over a year (705 tidal periods). As mentioned previously, the mean power output does not indicate too much by itself since tidal power is so uneven and indeed is zero about 50% of the time, but the value is quoted to give an idea of the average power yield. We have used km^2 as units of area for A since the formulas derived by Bernshtein, which we will use eventually, involve A in such units.

Table 3 Annual energy, mean power output at mean range and spring range available in various tidal basins located around Ungava Bay, assuming an efficiency of the plant of 30%

Site	Area	Mean area	Range	Annual energy output	Mean power output	Spring range	Mean power output at spring
		A	R	E_y	P	R_s	P_s
	km^2	km^2	m	10^9 kw-hr	MW	m	MW
Payne			6.97			9.32	
1	265-189	227		6.349	726		1,298
2	189-162	176		4.923	563		1,006
3	145-120	133		3.720	425		761
Ikattok	98- 74	86	8.17	3.305	378	10.40	613
Leaf			8.66			11.40	
1	358-211	284		12.263	1,403		2,431
2	500-312	406		17.530	2,006		3,475
3	559-354	456		19.689	2,253		3,903
Koksoak	130- 86	108	8.17	4.151	475	10.90	845
False River	164- 99	131	8.10	4.949	566	10.70	988
Whale	154- 94	124	7.86	4.411	504	10.40	883
George	164-145	154	7.07	4.432	507	9.10	840
Keglo Bay	48- 37	42	6.46	1.009	115	8.20	186
Abloviak Fiord	43	43	5.85	.847	97	7.40	155

3. The power potential of the rivers emptying into Ungava Bay

In general a river consists of a natural reservoir from which the water descends to sea level following a fairly well-established path. Tributaries make their contribution, steadily increasing the discharge. The mechanism driving the water is the stored potential energy which is gradually released as the water moves down to the sea. In flat open plains, this potential energy is beyond the reach of man, except perhaps for irrigation purposes, but in steep and deeply encased valleys, the river may be made to release all or part of its stored energy by impounding it behind a dam. The erection of a dam allows the storage of a considerable amount of water and makes it possible to release the water at rates determined by the power demand and the installed turbine capacity. The limitations to this flexibility are the capacity of the reservoir and its rate of siltation. A small reservoir will force the release of water even when there is no demand for power. A large reservoir might take many years to fill and create local geological instability, but it would allow greater flexibility. The establishment of a large reservoir in populated areas might cause the loss of valuable land, the displacement of population and rather distressing areas of irregularly wetted territory.

The shape of Ungava Bay and the topography of the terrain surrounding it are such that quite a few rivers of relatively high discharge empty into it. They have been noted (Figure 1) as the Payne, the Leaf, the Koksoak, the Whale and the George Rivers. With the exception of the Payne, they all have their sources inside the Labrador plateau which stands over 500 m above mean sea level. All of them run in deeply encased U shaped glaciated valleys and, with the exception of the Whale, there is no difficulty in finding suitable sites for their impounding. In the case of the Leaf and the Payne, a single barrage could adequately exploit the bulk of the potential energy of the river. The reservoirs in the head waters on the other hand, have rather fuzzy boundaries and will have to be sharpened by the construction of quite a few dykes in order to help define in which direction the water will flow.

The amount of power generated by the release of Q m^3/sec of water from a height of D meters is given by

$$P = \rho g D Q \text{ kw} \qquad (3)$$

where D = head (in m) and Q = discharge (in m^3/sec).

The head waters of all the rivers stand at around 500 m of altitude and any cubic metre of water descending from such a height to sea level would yield 5 MW of power. Their combined discharge being 4,300 m^3/sec (Anon., 1971), their gross power potential should be of the order of 20,000 MW. A closer scrutiny of suitable sites for barrages and reservoirs will reduce this estimate to about 12,000 MW, which is still a very large amount of power.

We will now review each of the rivers mentioned. In Table 4 we list the important parameters of the hydro plants which could be erected on the rivers as well as the storage capacities of the working water mass of the reservoir. The quantities quoted are orders of magnitude only, since only a more detailed survey could determine them more accurately. Closer engineering studies might also alter the position of the dam sites and most likely increase the power yields. The data were derived from topographic charts where the elevations were contoured in feet, while the discharge extracted from Anon., 1971 were quoted in ft^3/sec. We have entered these figures in brackets in the table but we had to transform them into metric units in order to be able to embody them in our calculations. Figures 6 to 9 show the actual course of the river by a thin line and the flooded areas by thicker lines (stars denote the sites of dykes).

Figure 6 shows the Payne River system. The drainage in Payne Lake is undefined and some dykes will have to be built in its western end if a level of over 170 m is to be maintained there. The topography around Payne Lake is that of a saddle and its waters can flow equally well either towards Povungnituk Bay in Hudson Bay or Payne Basin in Ungava Bay. No other geographical problem seems to be present and a single dam in the Payne estuary would drain nearly the whole energy of the river.

The Leaf River system (Figure 7) is equally simple. The same problem arises in Lake Minto as in Payne Lake and it is evident that dykes will have to be set up at its western end to define its drainage. At first sight, it seems that the level can be maintained at 180 m without too much difficulty; closer studies might even raise this figure to 210 m. Beyond Lake Minto the river bed is sharply defined and a single dam a little way from the estuary could tap the bulk of the energy.

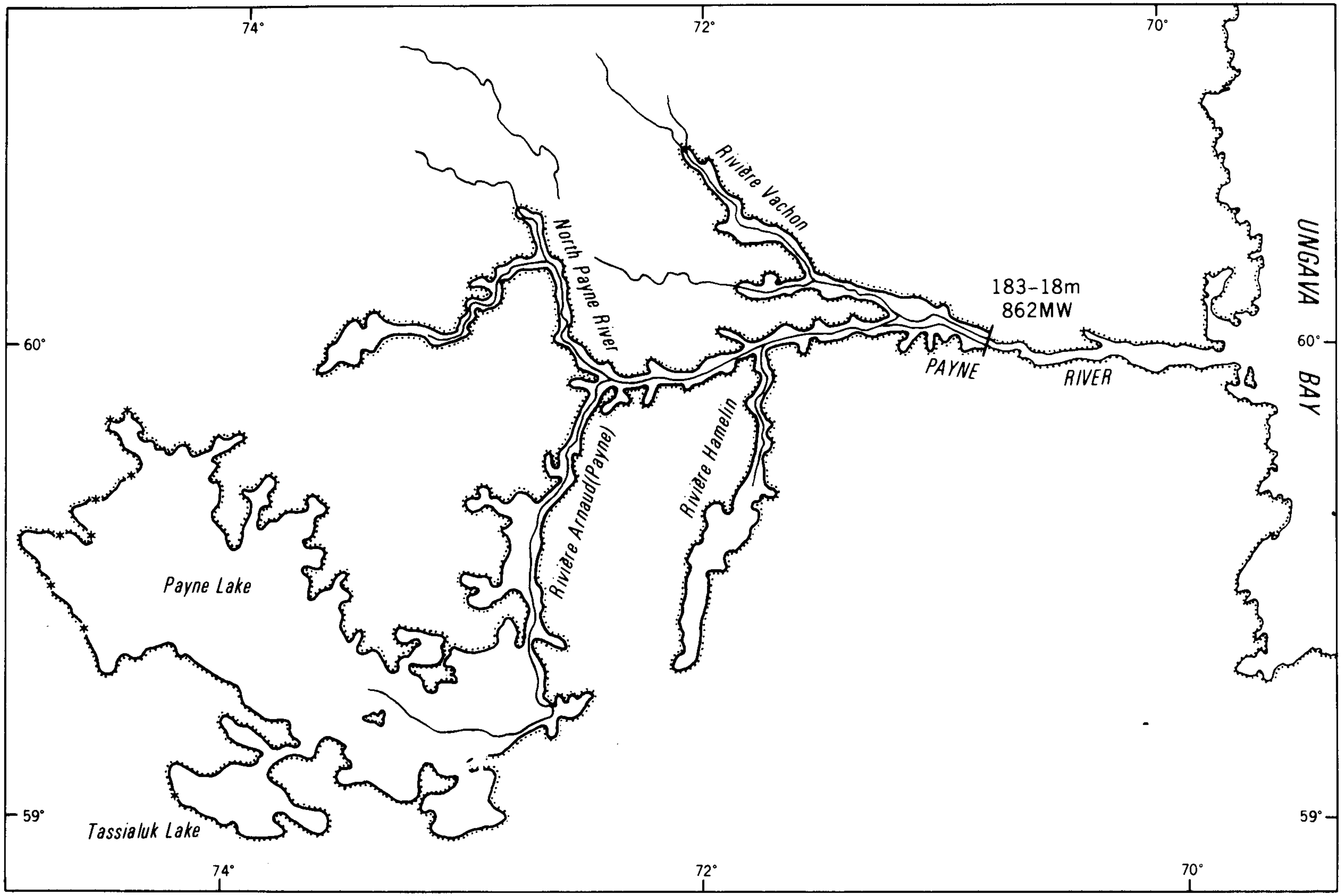

Fig. 6 The Payne River system. The fine lines delineate the actual width of the river; the thick lines the limits of the flooded areas. The stars denote sites of indifferent drainage where dykes will have to be constructed. The drop in level at the dam site will be from 183 to 18 meters and the gross power output expected at the dam site is 862 MW.

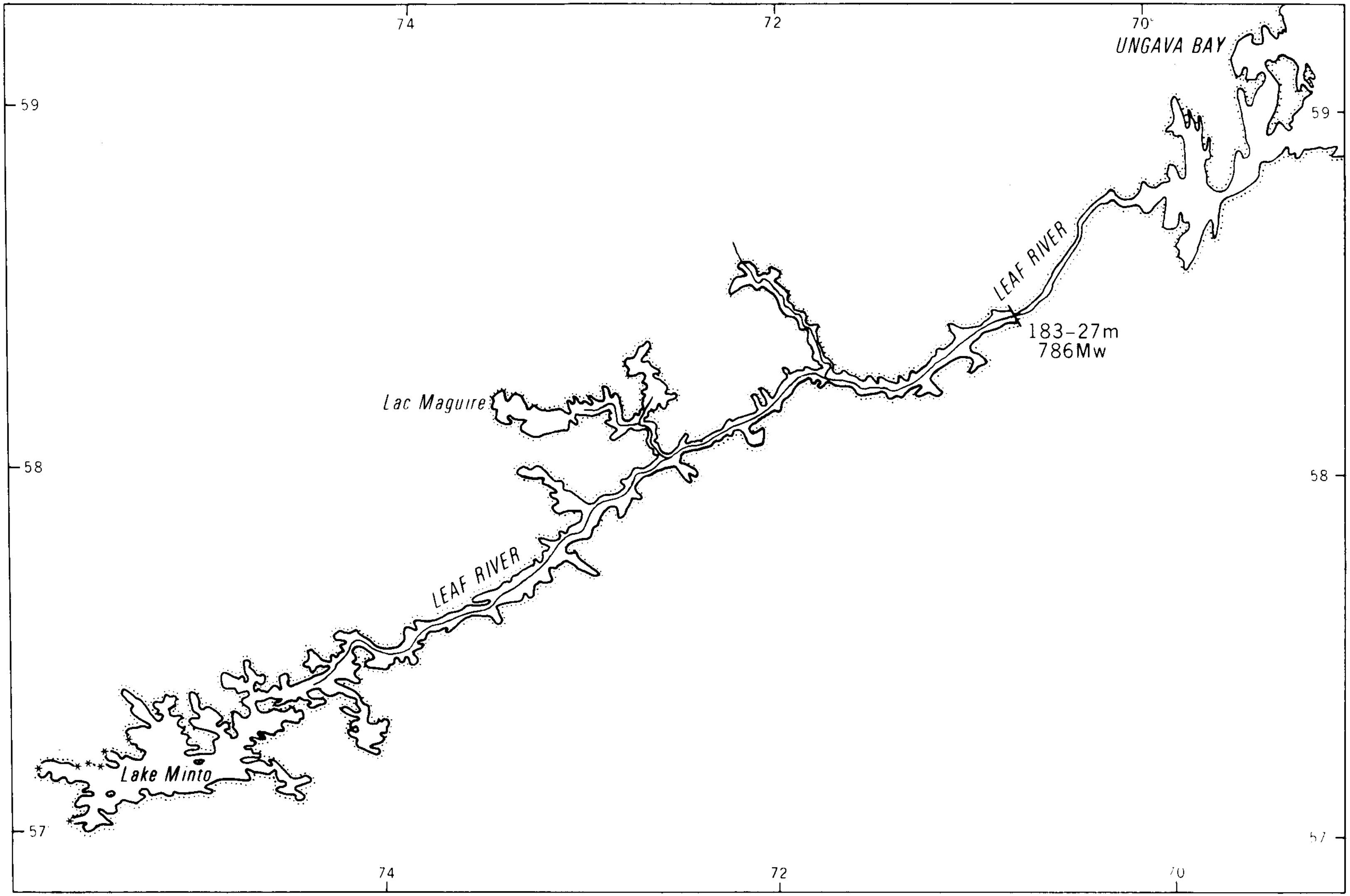

Fig. 7 The Leaf River system.

The drainage of the upper waters of the Kaniapiskau River (Figure 8) is quite undefined. A safe height for the water level of the reservoir is about 520 m; then Lac Delorme could perform as the reservoir. The level of Lake Kaniapiskau would stand slightly higher. The waters of Lac Delorme have a tendency to flow into the La Grande Rivière system and dykes would have to be erected in the areas of Lac Brion and Lac Cognac (54°40'N, 70°10'W).

The James Bay Power Development Corporation, in its preliminary plans for the exploitation of the La Grande Rivière system, will attempt to direct the head waters of the Kaniapiskau, namely Lake Kaniapiskau and Lac Delorme, into the La Grande system. This would imply a reduction of about 40% in the mass of water flowing down the Kaniapiskau. Such an undertaking might be feasible although at first sight it seems far from easy. The drainage is extremely undefined in that area but somehow the water manages eventually to converge by its own resources into the Kaniapiskau River. It may be preferable to reserve the waters of Lac Delorme and Lake Kaniapiskau for the future exploitation of the Koksoak system. Once the Kaniapiskau takes shape, it follows a sharply defined course down to sea level.

A first barrage could be established at a constriction 20 km below the Upper Gorge where a gross head of about 160 m could be maintained. This site is only 150 km from Schefferville, but the terrain between the two is very mountainous and consists of a multiplicity of hills about 600 m high around which shallow streams and rapids flow; a large number of bridges and culverts

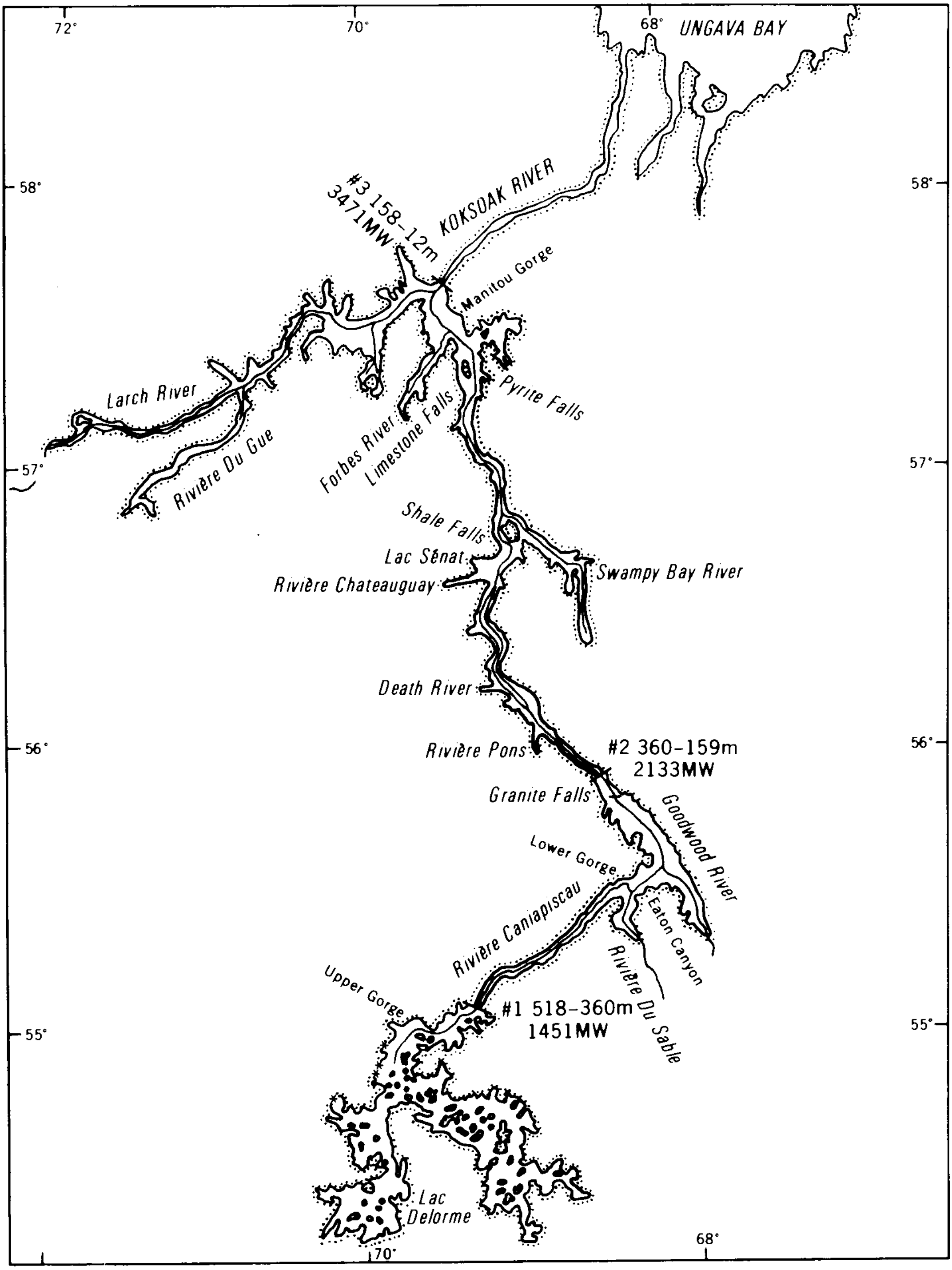

Fig. 8 The Koksoak River system.

would be required to build a land connection between the two points.

A second site favourable for power generation is located 10 km below the Granite Falls, where the level behind the dam could be maintained at 360 m without undue difficulty and a gross head of 200 m could be established.

The third and last site is on the Koksoak River about 5 km below the junction of the Larch and Kaniapiskau Rivers and 200 km away from site 2. The volume of water retained at a level of 158 m would be very large and no special structure would be required except the dam itself. From the combined discharge of the Larch and Kaniapiskau, nearly 3,500 MW could be generated at this point. If the waters of Lac Delorme and Lake Kaniapiskau were directed into the La Grande system, it would still be possible to generate 2,100 MW. Land access to site 3 seems possible only from Fort Chimo with perhaps a road running along the Kaniapiskau joining all three sites. The course of the river is interrupted by major falls and is not favourable to navigation. Rock material might be available from the neighbouring hills and gravel from the river bed. From any point of view, the Koksoak appears as a large reservoir of hydro energy which will remain highly attractive as long as hydro power remains economic.

In contrast to the other rivers, the main part of the Whale River flows in a broad valley where the construction of a barrage would be prohibitive. Further upstream, in a narrow bend just before its junction with the Wheeler River, a head of about 100 m could be maintained. Because of the relatively slight discharge at that point (280 m^3/sec), the power yield of about 250 MW would be relatively small. In view of the high energy potential of the other rivers, we do not consider it worthwhile to further look at the Whale River.

In contrast to the Whale, the George (Figure 9) is well organized from its headwaters down to sea level. A first barrage could be established below a double bend in the Hades Hills. The water could be backed to a height of at least 460 m; a level which could be maintained everywhere with the help of two small dykes. One of them would prevent the Rivière du Pas from overflowing into Lac Tudor, while the second would define the head waters of Lac Dihourse which, in spite of the defined Québec-Labrador border, seems to enjoy flowing in both directions depending on the time of the year. A second dam could be laid 85 km north of site 1 in a deeply encased section and the third, 50 km beyond, could wring a few extra kilowatts out of the George if the soil conditions allow. Access to the three sites, either from the south or from the north, is not easy. A ship route through Ungava Bay seems the only possible choice with a road developed southward along the George. The former settlement of George River could be revitalized to act as a base during the development operations.

Table 4 summarizes the information relevant for the exploitation of the hydraulic energy of the rivers just reviewed in this section.

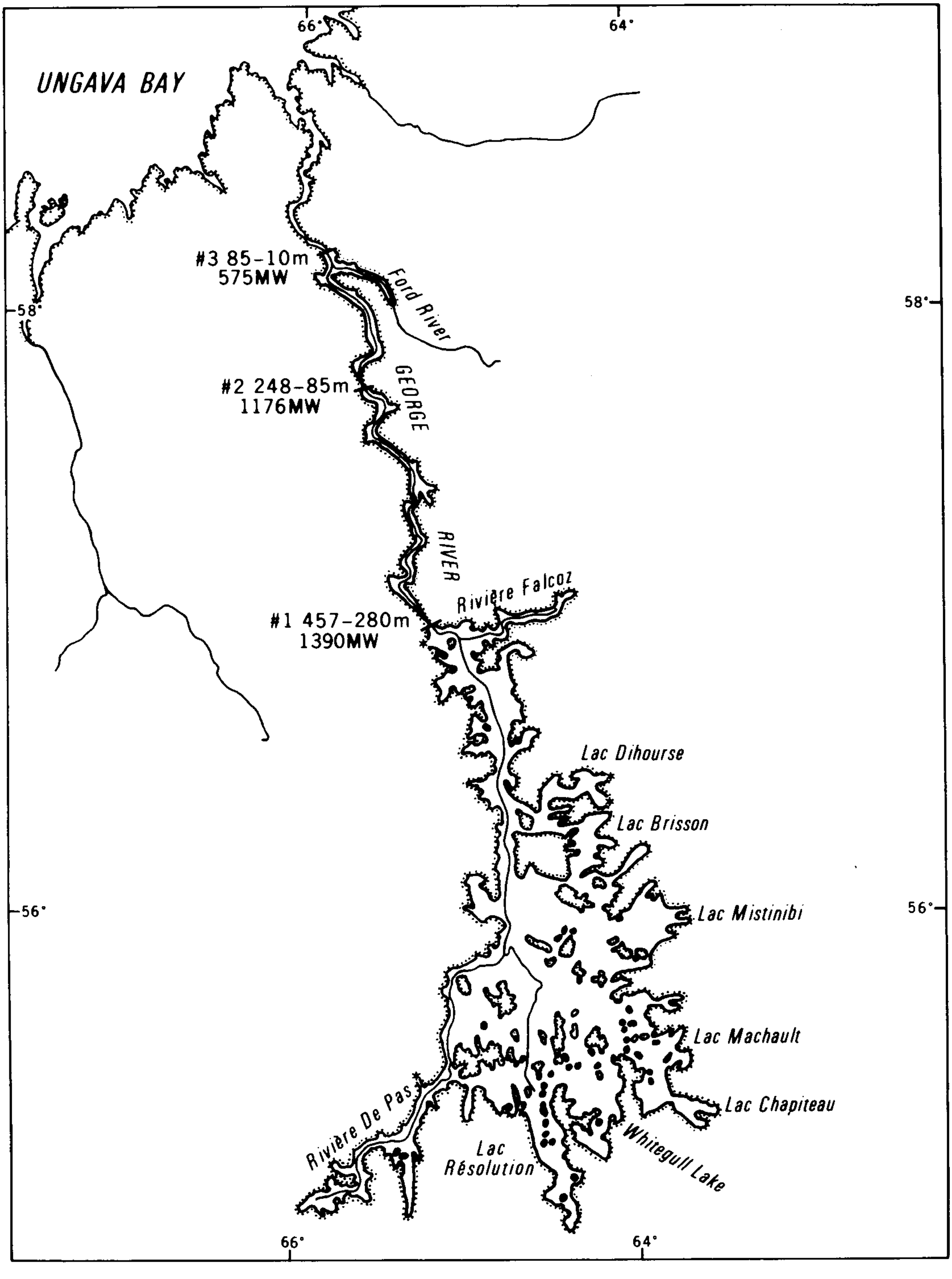

Fig. 9 The George River system.

Table 4 Power potential of the major rivers emptying into Ungava Bay [+]

Name	Drainage area km^2	Dam site		Dam width km	Drop m(ft)	Head H m(ft)	Mean discharge Q m^3/sec(ft^3/sec)	Flooded area km^2	Volume capacity at 20 m drawdown km^3	Time necessary to discharge water at mean Q days	Power output individual plant MW	Total power output for river MW
Payne (Arnaud)	34,200	60°02'N	70°45'W	3.8	183-18 (600^--60)	165(540)	535(18,900)	5458	109.2	2362 (6.5 years)	862	862
Leaf	41,700	58°29'	70°45'	2.5	183-27 (600^+-90)	156(510)	569(20,100)	3475	69.5	1414 (3.9 years)	865	865
Koksoak	144,500											
Dam 1		55°38'	68°10'	4.2	518-360 (1,700-1,180)	158(520)	934(33,000)	2138	42.8	530	1,451	
Dam 2		55°35'	68°30'	4.8	360-159 (1,180-520)	201(660)	1082(38,200)	899	18.0	192	2,133	
Dam 3		57°42'	69°26'	2.9	158-12 (520-40)	146(480)	2421(85,500)	5561	111.2	532	3,471	7,055
*Dam 2						201	147(5,200)				290	
*Dam 3						146	1487(52,500)				2,130	2,421
George	35,200											
Dam 1		56°58'	65°10'	2.5	457-280 (1,500-815)	209(685)	680(24,000)	3108	62.2	1056 (2.9 years)	1,390	
Dam 2		57°45'	65°37'	2.0	248-85 (815-280)	163(535)	736(26,000)	266	5.3	83	1,176	
Dam 3		58°13'	65°48'	2.1	85-10	76(250)	773(27,300)	147	2.9	43	575	3,141

[+] All the figures given in this table are approximate and are meant only to supply orders of magnitude

* Assuming that the waters of Lakes Kaniapiskau and Delorme are diverted into the la Grande Riviére system

4. The combination of river power and tidal power

4.1 The installed capacity in a tidal plant

Since we wish to integrate the output of a tidal plant with other more controllable sources of energy we will strive to extract the maximum possible energy from the tide. The theory of such a scheme of exploitation has been elaborated by Gibrat (1953) and allows the quantitative evaluation in time of all the parameters involved in such an operation. It requires precise information on the type of turbines to be installed, on the tide and on all the variables of the basin. In our case, we have only some vague information on the basins in Ungava Bay and it would be premature to decide on the specific type of turbine that could be used there. It is more sensible then to utilize some general formulas which have been derived by Bernshtein (1965) for a basin one km^2 in area, with a tidal range of 5.4 m, related to the maximum possible yield of energy, assuming a turbine efficiency of 71%. These formulas are expressed in terms of the range R in meters and the area A in km^2. They have no pretention of being overly accurate but they certainly are more than adequate for preliminary planning.

The suitable initial head, H_{init}, was found to amount to

$$H_{init} = 0.46 \text{ R meters} \tag{4}$$

or nearly half the tidal range as had been suggested by various other authors (Davey, 1923). From the results of the calculations with the 5.4 m tide, the maximum head during one cycle of exploitation was found to be 1.1 H_{init} or

$$H_{max} = 0.51\ R \tag{5}$$

Since the largest tides are about 53% larger than the average tide (see Table 2), the largest maximum head should be of the order

$$H_{max,max} = 0.78\ R \tag{6}$$

The optimum discharge was found to be 250 m^3/sec so that in general

$$Q_{optimum} = 46\ RA\ m^3/sec \tag{7}$$

For the largest tide, the discharge would be raised by 23% since it essentially depends on $\sqrt{gH}$ so that

$$Q_{max} = 57\ RA \tag{8}$$

For turbines operating at 71% efficiency, this would imply an installed capacity of

$$N_i = 0.71 x 9.8 x Q_{max} x H_{max,max} = 311\ R^2A\ kw \tag{9}$$

The maximum power output at neap tide will be

$$N_{max}(neap) = N_i/(1.23)^2 = 162\ R^2A\ kw \tag{10}$$

The initial output at H_{init} is, therefore,

$$N_{init} = 150\ R^2A\ \text{kw} \qquad (11)$$

For the minimum output which occurs at a range 0.47 R

$$N_{min} = 54\ R^2A\ \text{kw}$$

with

$$N_{min,init} = 49\ R^2A\ \text{kw} \qquad (12)$$

For a plant of 30% efficiency, the yearly energy output is, from equation 2

$$E_y = 5.9\text{x}10^5\ R^2A\ \text{kw-hr} \qquad (13)$$

With its actual power output the plant would require between E_y/N_i and E_y/N_{init} hrs to produce such energy, i.e. between 1,897 and 3,933 hrs, which implies a rate of utilization of the turbines lying between 22 and 45%. This very low rate is one of the unavoidable features of a tidal plant.

We notice at this stage that all the basic formulas related to a tidal plant depend on the range R and the surface area A. In particular, the important quantities, E_{total}, the mean power output P, the installed capacity N_i and the yearly energy output E_y depend on the product R^2A. Thus

$$E_{total} = 2.72\text{x}10^3 \; R^2A \text{ kw-hr}$$

$$P = 66 \; R^2A \text{ kw}$$

$$N_i = 311 \; R^2A \text{ kw}$$

$$E_y = 5.9\text{x}10^5 \; R^2A \text{ kw-hr}$$

E_{total} is the energy present in the tide during a whole tidal cycle and P represents the average power that can be extracted from it. The ratio of N_i to P is about 5:1. This may seem exaggerated at first, but it is to be realized that turbines are not generating during the whole tidal period and that they have to cope with the largest tides.

We can use these formulas to obtain an idea of the installation necessary for the exploitation of the sites mentioned in Table 1. Table 5 gives the installed capacity, the initial and maximum power output during a cycle, the maximum discharge through the turbines and the operating head range. We also compute the maximum possible water velocity and in turn the minimum throat area of the turbines necessary to pass the volumes of water contemplated.

Table 5 Basic parameters of the tidal plants that could be installed in various basins on the periphery of Ungava Bay

Site	Installed capacity	Initial power output for mean range	Max power output during the same cycle	Maximum discharge	Range of head	Induced velocity at maximum head	Throat area of the turbines necessary to to accommodate Q_{max} assuming losses of 10%
	N_i	N_{init}	N_{max}	Q_{max}	$H_{init} \rightarrow H_{max,max}$	$\sqrt{gH_{max,max}}$	S
	MW	MW	MW	$x10^4 m^3/sec$	m	m/sec	m^2
Payne							
1	3,423	1,654	1,820	9.02	3.2→5.4	7.3	13,877
2	2,655	1,280	1,383	7.00			10,764
3	2,007	968	1,045	5.29			8,134
Ikattok	1,786	862	931	4.01	3.8→6.4	7.9	5,645
Leaf					4.0→6.8	8.2	
1	6,623	3,196	3,450	14.02			19,210
2	9,469	4,568	4,932	20.04			27,456
3	10,634	5,129	5,539	22.51			30,841
Koksoak	2,239	1,080	1,166	5.03	3.8→6.4	7.9	7,085
False River	2,675	1,290	1,393	6.05	3.7→6.1	7.7	8,643
Whale	2,382	1,149	1,241	5.56	3.6→6.1	7.7	8,058
George	2,393	1,154	1,247	6.21	3.3→5.6	7.4	9,409
Keglo Bay	545	263	284	1.55	3.0→5.1	7.1	2,460
Abloviak Fiord	458	221	238	1.43	2.7→4.6	6.7	2,424

4.2 The turbines

The turbine that could best exploit tidal energy should be a low-head, large-capacity turbine, i.e. it should pass very large quantities of water under heads which seldom exceed 5 m. A sophisticated bulb type, horizontal flow turbine has been used in the Rance and Kislaya projects; it may also operate either as a pump (but with much reduced efficiency) or as a sluice.

Pumping increases the energy production of a tidal plant (Gibrat, 1966; Godin, 1969) but complicates the installation and maintenance appreciably. Since a large number of turbines will be installed in any of the tidal plants contemplated in Ungava Bay and since they will be used exclusively to supply massive blocks of power without ever making any demand on the electric network, we shall avoid considering pumping. However, we will retain the double flow features of the turbines, i.e. we wish them to generate power either on emptying or filling of the tidal basin since in this way 40% more energy can be generated from the same installation than when generating on emptying only.

The bulb turbine carries its generator in its hub, but it would be preferable if this bulb were away from the throat area in order to increase the discharge capacity of the turbine. The straight flow turbine has been suggested (Braikevitch, 1972; Ruus, 1972) which consists of a runner transmitting its mechanical energy at the tip of its blades. This seems far-fetched but contemporary technology appears in a position to cope with the problems associated with such a device. If this turbine could be mass produced and made to operate both ways, much progress will have been accomplished in finding the type of turbine appropriate for the exploitation of tidal energy. In any case, the power generated by a turbine depends on the flow of water through it and the effective head under which this occurs. If we call the efficiency of the turbine, k, the power it generates will be given by

$$P = \rho kgQH \text{ kw} \tag{14}$$

Hydraulic turbines can have a very high efficiency, but in the case of tides, conditions can seldom be maintained so that they perform at their peak efficiency. An efficiency of 70% is a realistic value to expect in this case and we write equation 14 as

$$P = 7\ Q\ H \text{ kw} \tag{15}$$

as Bernshtein does.

The discharge Q is determined by the head H and the effective throat area of the turbines. The velocity of water inside has to be less than

$$v = \sqrt{gH} \text{ m/sec} \tag{16}$$

since head losses are unavoidable. We may take these losses as 10% so that v inside the turbine is about 5% less than equation 16. As an order of magnitude of Q, we get

$$Q \simeq 3H^{\frac{1}{2}}S \text{ m}^3/\text{sec} \qquad (17)$$

where S is the net area of the water passage inside the turbine. In our case H is limited by nature, therefore, we should strive in the design to make S as large as possible. However, practical limitations restrict the size of S so that we have to increase the number of units which in turn implies an increase in the length of the barrage.

From the maximum possible head and the implied discharge, we may deduce the maximum rating of the turbine if we know its net open area S; this quantity in turn determines the number of such turbines necessary for the installed capacity N_i. If we consider the straight flow turbines described by Ruus (1972, page 393) with a runner 12 m in diameter and a net throat area of $93 m^2$, we may evaluate the number of such turbines necessary in the installations described in Table 5, assuming that they can be made to generate both ways. In Table 6, we list the rating of the turbine deduced from Table 5, the number required and the length of dam they require assuming that each unit occupies 24 meters of width.

Table 6 Number of straight flow turbines required to supply the installed capacity and the length of dam they will occupy

Basin	Installed capacity MW	Maximum rating MW	Number	Necessary length of dam required km
Payne				
1	3,432	26	132	3.168
2	2,600	26	100	2.400
3	1,976	26	76	1.824
Ikattok	1,716	33	52	1.248
Leaf				
1	6,624	36	184	4.416
2	9,504	36	264	6.336
3	10,656	36	296	7.104
Koksoak	2,244	33	68	1.632
False River	2,604	31	84	2.016
Whale	2,356	31	76	1.824
George	2,376	27	88	2.112
Keglo Bay	552	23	24	0.576
Abloviak Fiord	480	20	24	0.576

4.3 The closure of the tidal basins

We had indicated tentatively in Figure 1 the location of the closures in the tidal basins. In this way we could compute their approximate power potential (Table 3), the number of turbines to be installed and the width of barrage they would require (Table 6). With this information on hand we can go back to the sites and attempt to delineate as accurately as possible the location and width of these closures using the nautical charts issued by the Canadian Hydrographic Service. These charts give a good coverage of the depths of Payne Basin, Leaf Basin and the entrance to the Koksoak River; they give no soundings for Ikattok Bay, False River, Whale River, George River, Keglo Bay or Abloviak Fiord.

In Payne Bay, three closures appear possible (Figure 10). The most outward would link Savik Point to Kidlipait Islet with additional dykes linking the Islet with Ivik Island and the mainland. The main closure would have a length of 8.1 km while the others would add 3.3 km. The depths are not large anywhere with an average of less than 10 fathoms, the maximum being 20 fm. From the work of the Atlantic Tidal Power Programming Board, it appears that a depth of 13 fm is required for the siting of the turbine housing; there is, therefore, ample space to install all the turbines required and even sluices if they ever are required (Figure 11a). If the exposure at this site is not too severe and if the bottom is of solid rock, it would be the most favourable site to extract the maximum energy from Payne Basin.

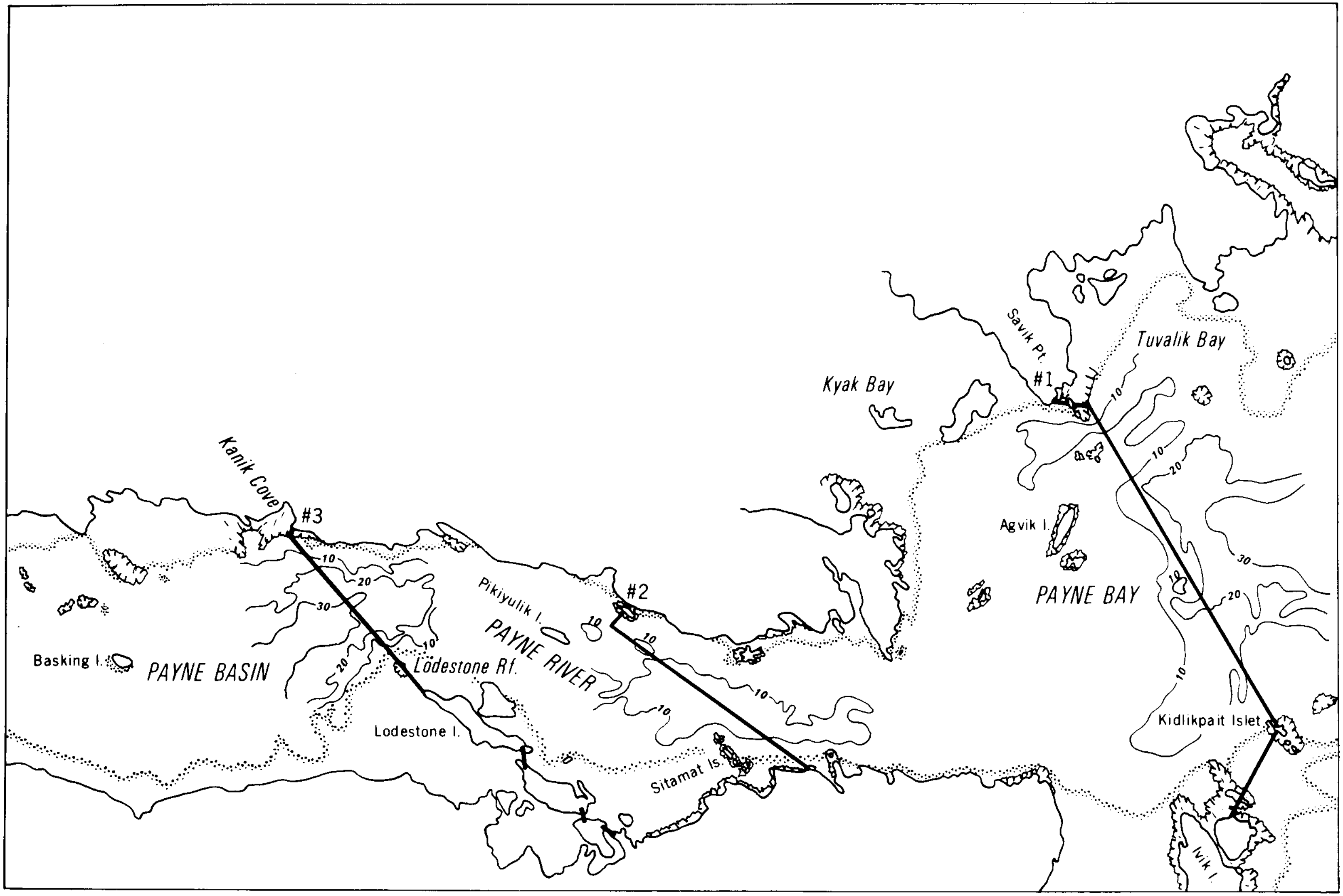

Fig. 10 Three possible closures of Payne Basin for the generation of tidal power.

Fig. 11 a), b) and c). Horizontal cross sections of the three possible sites. The dashed lines denote either filling or excavating depending on their orientation.

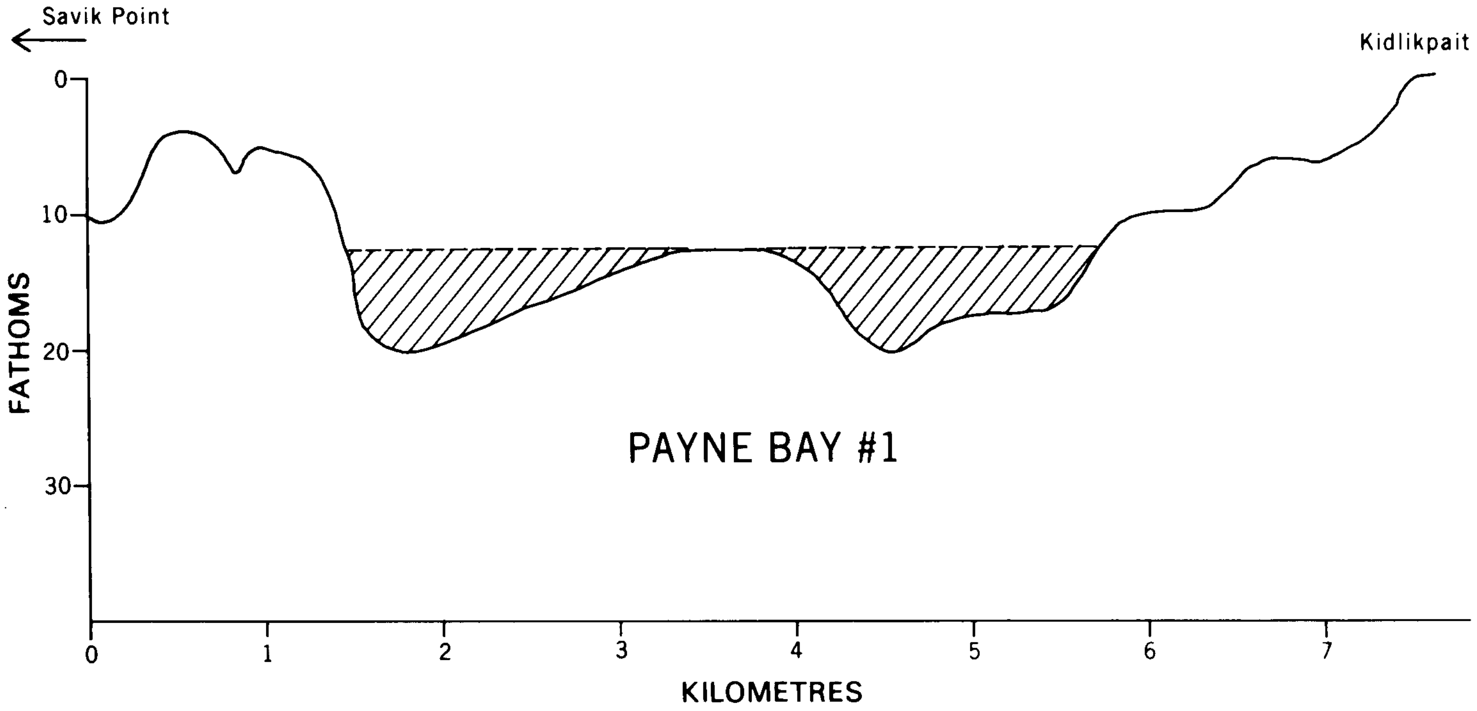

Fig. 11(a)

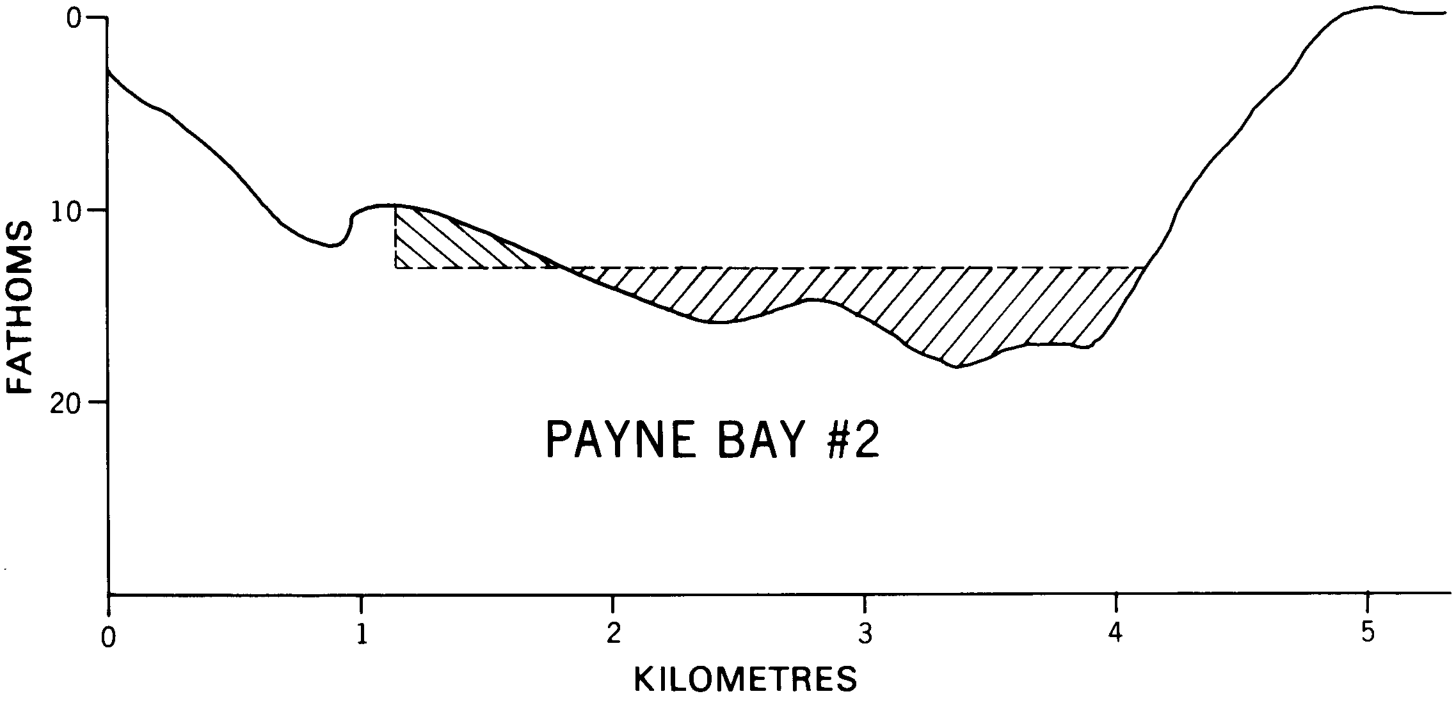

Fig. 11(b)

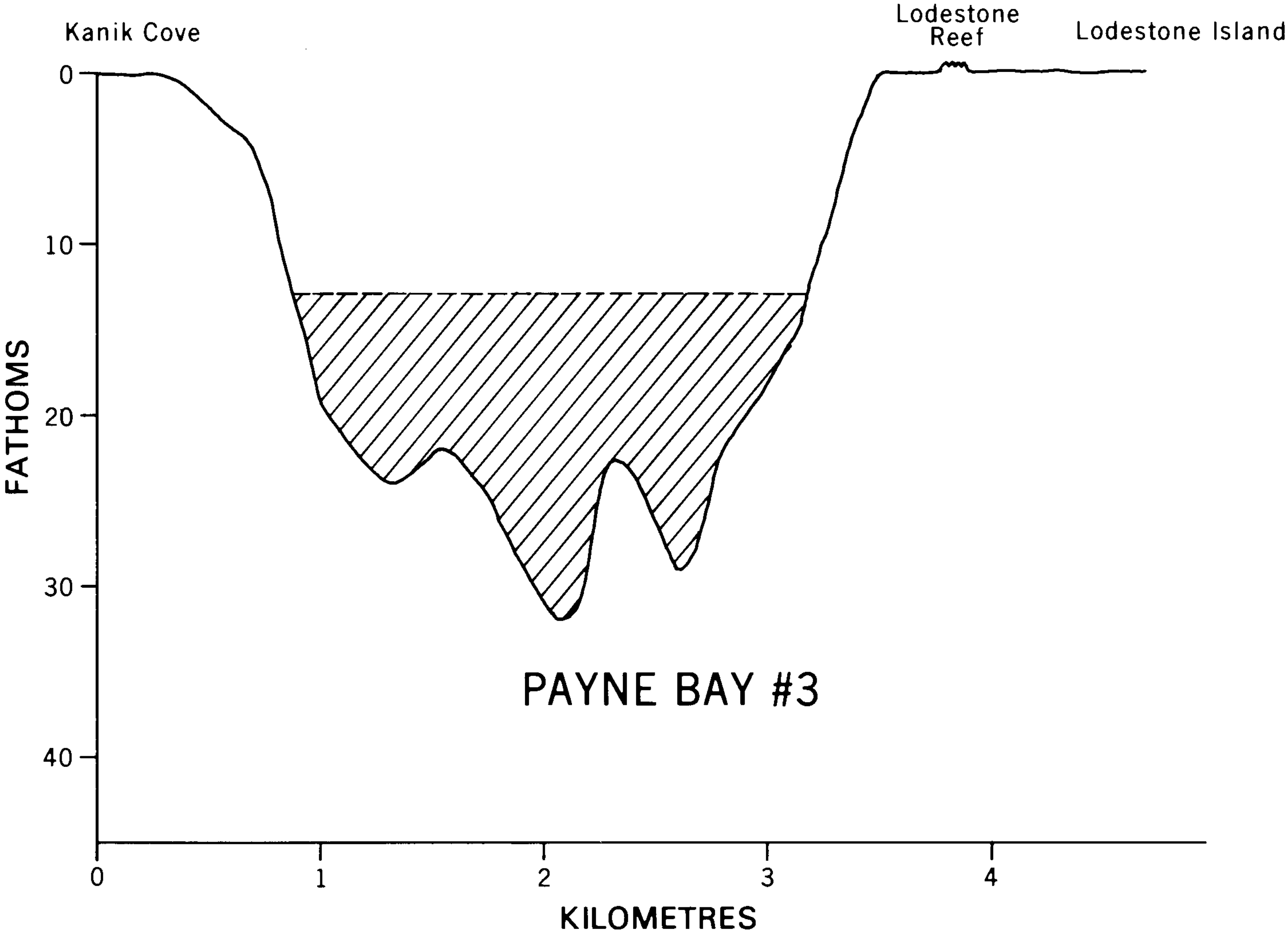
Kanik Cove
Lodestone Reef
Lodestone Island
FATHOMS
0
10
20
30
40
PAYNE BAY #3
0
1
2
3
4
KILOMETRES

Fig. 11(c)

The second closure had to be laid obliquely because of the width required to house all the necessary turbines (Figure 10). The section (Figure 11b) indicates 2.35 km of width deeper than 13 fm and as 2.40 km would be required to house the generating units some slight excavations on the northern side would be required.

The innermost closure would run over much deeper water than the previous two with depths of up to 32 fm but its sheltered position might make it more advantageous than the others. A fair amount of filling would be necessary and the return in energy would be less than the other projects (Figure 11c).

As soundings are not available for Ikattok Bay, the choice of a suitable closure cannot now be made. The width at the mouth is 8.96 km, much more than would be needed to house 1.2 km of turbines. Further inside, the barrage could straddle a string of islands, diminishing by a factor of 5, the width necessary. The approaches to Ikattok Bay seem extremely dangerous and no approach channel has been found.

The first possible closure in Leaf Basin (Figure 12c) would lie in a very sheltered position and would extend from Algerine Point to Whale Back Reef and continue easterly toward Trading Post Cove. The total width would be 6.5 km of which 5.0 km would have a depth in excess of 13 fm which could easily be extended to 5.4 km with some excavating (Figure 13a). Unfortunately the channel between Algerine Point and Whale Back Reef is very deep, reaching a maximum depth of 53 fm and would require much filling. This is one of the unfavourable features of this plan.

Fig. 12 a), b) and c). Possible closures of Leaf Basin in Leaf Bay, Leaf Passage and the inner Leaf Basin. Two alternatives are possible in Leaf Passage.

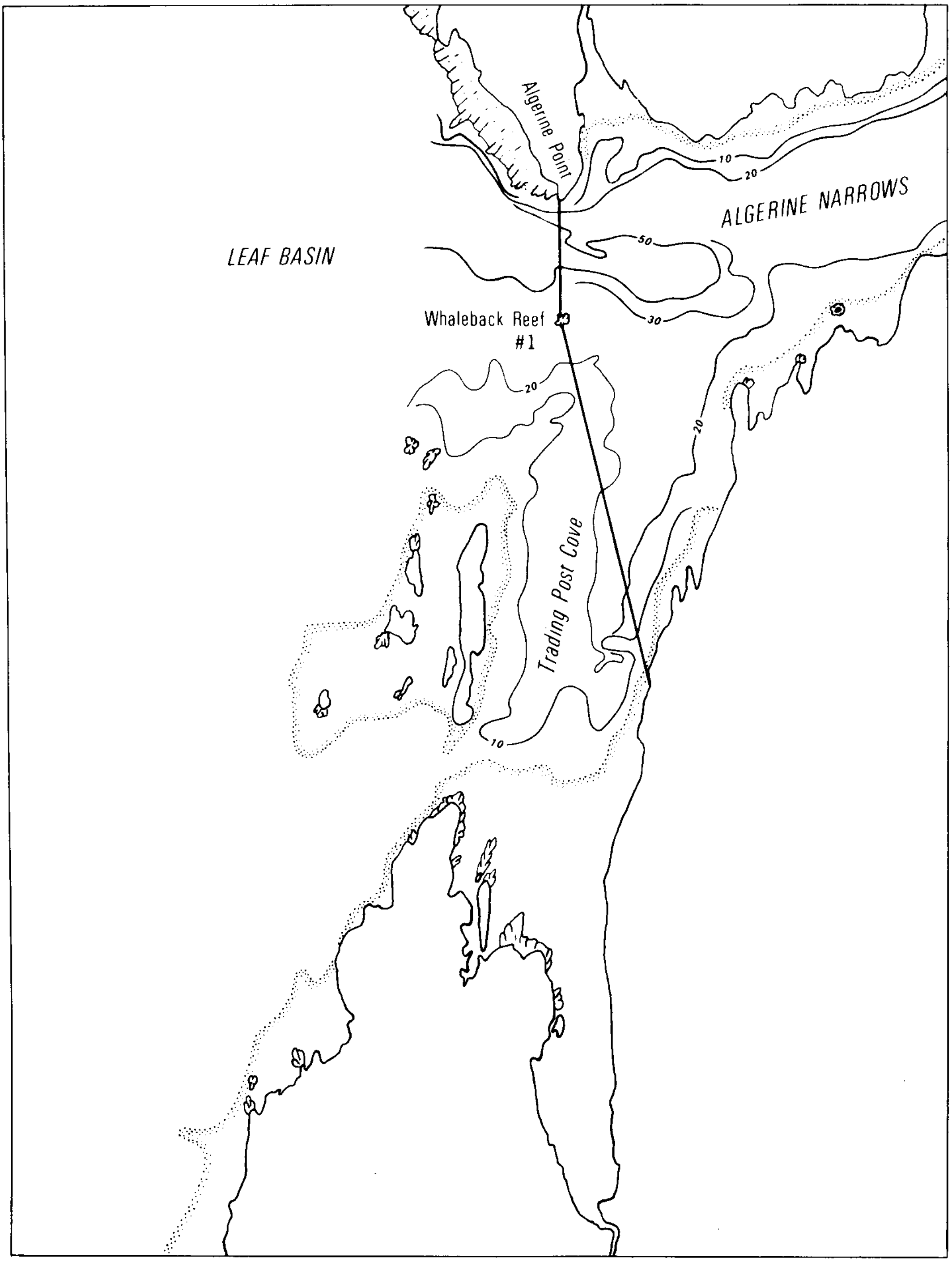

Fig. 12(a)

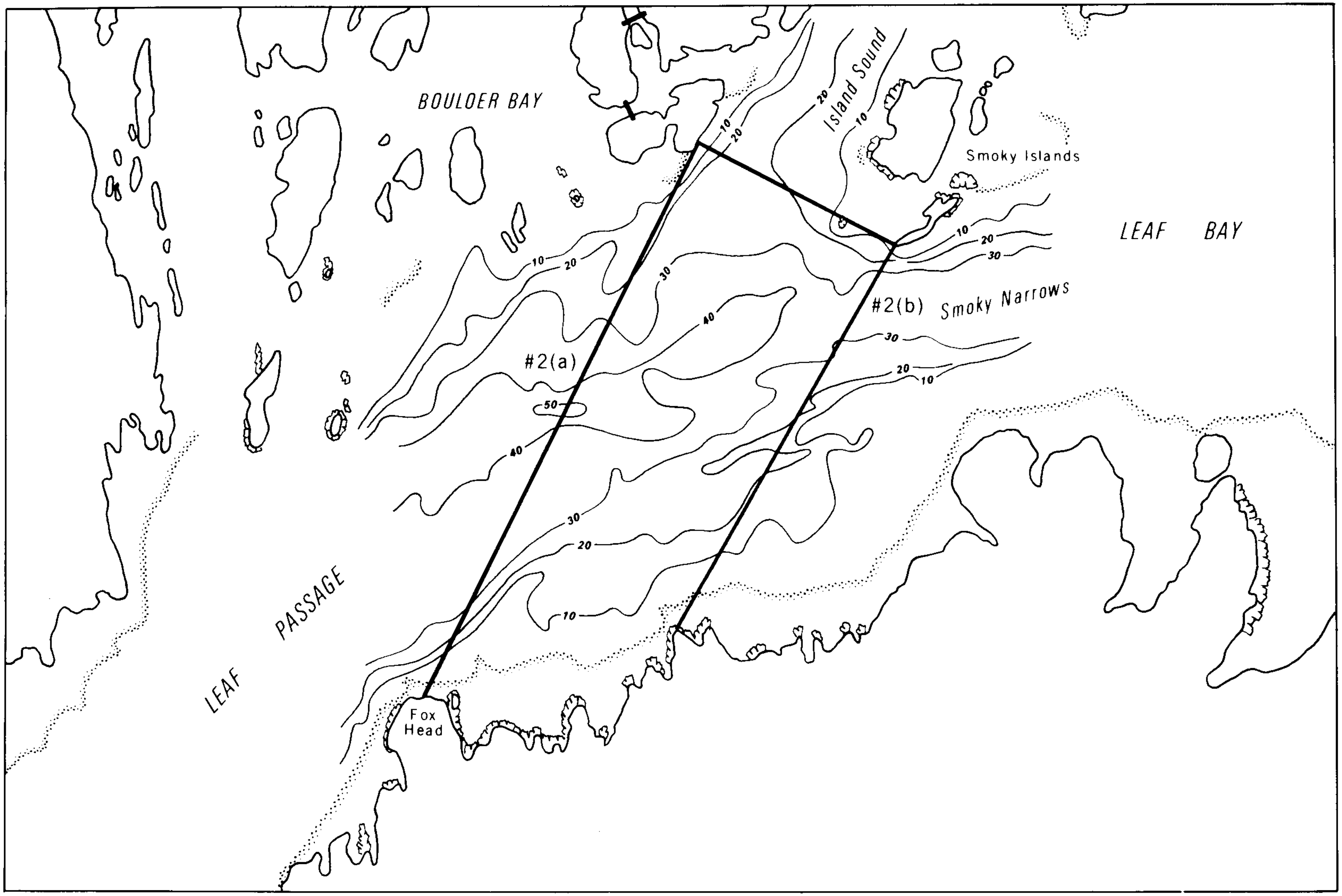
BOULDER BAY
Island Sound
Smoky Islands
LEAF BAY
#2(b)
Smoky Narrows
#2(a)
LEAF PASSAGE
Fox Head
10
20
30
40
50

Fig. 12(b)

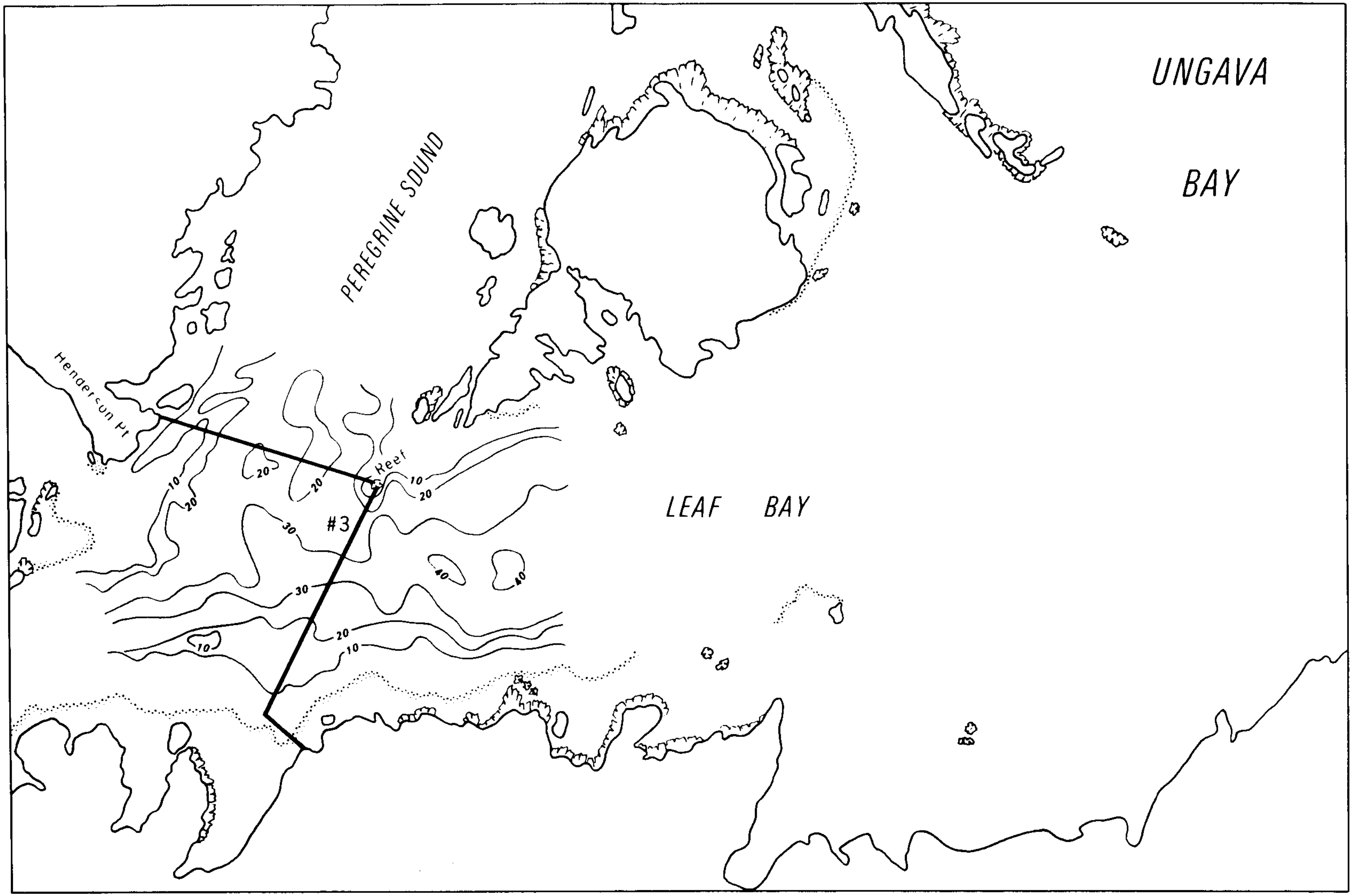
UNGAVA
BAY
PEREGRINE SOUND
LEAF BAY
Henderson Pt
Reef
#3
10
20
20
20
10
20
30
40
40
30
20
10
10

Fig. 12(c)

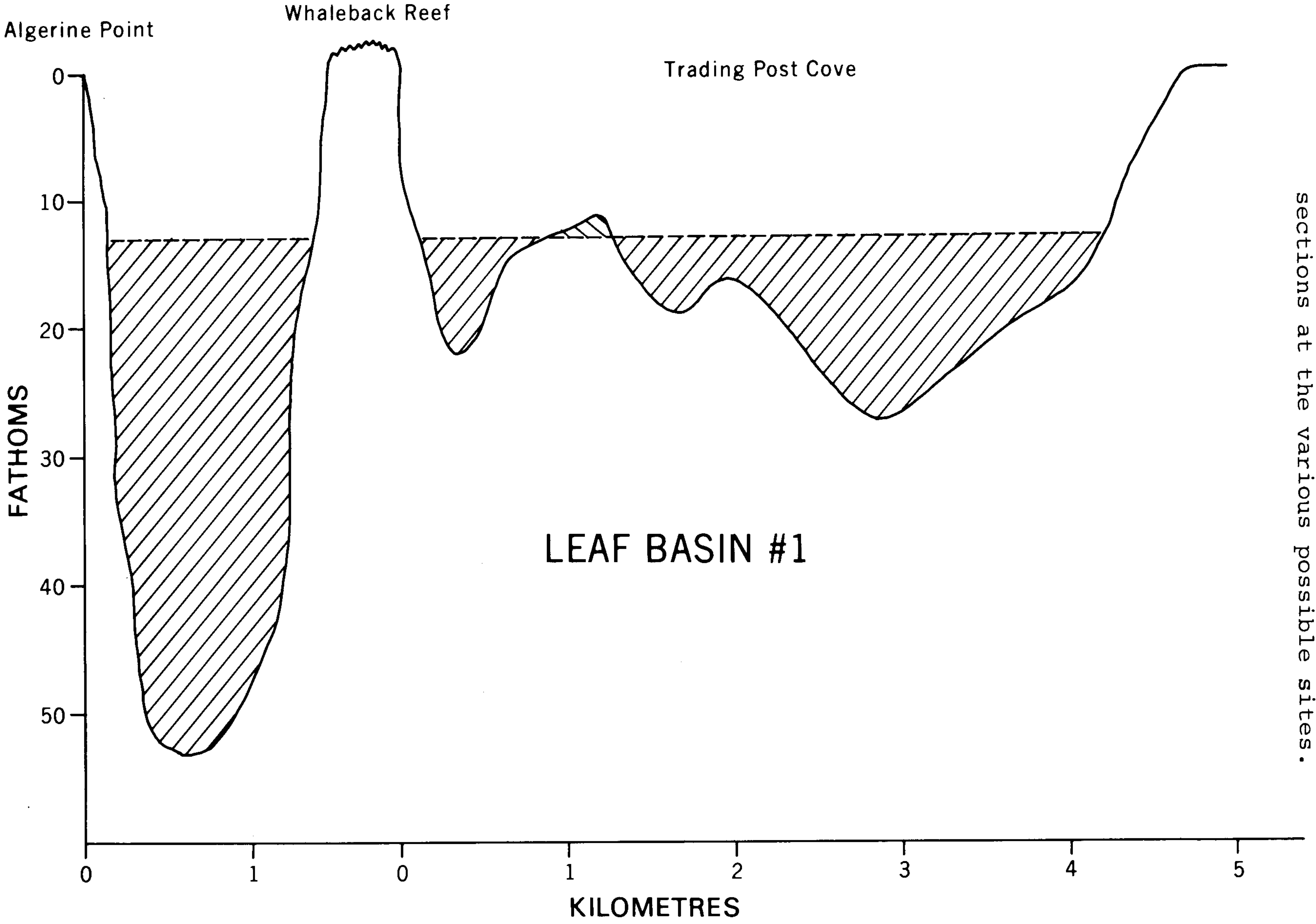

Fig. 13(a)

Fig. 13 a), b), c) and d). Horizontal cross sections at the various possible sites.

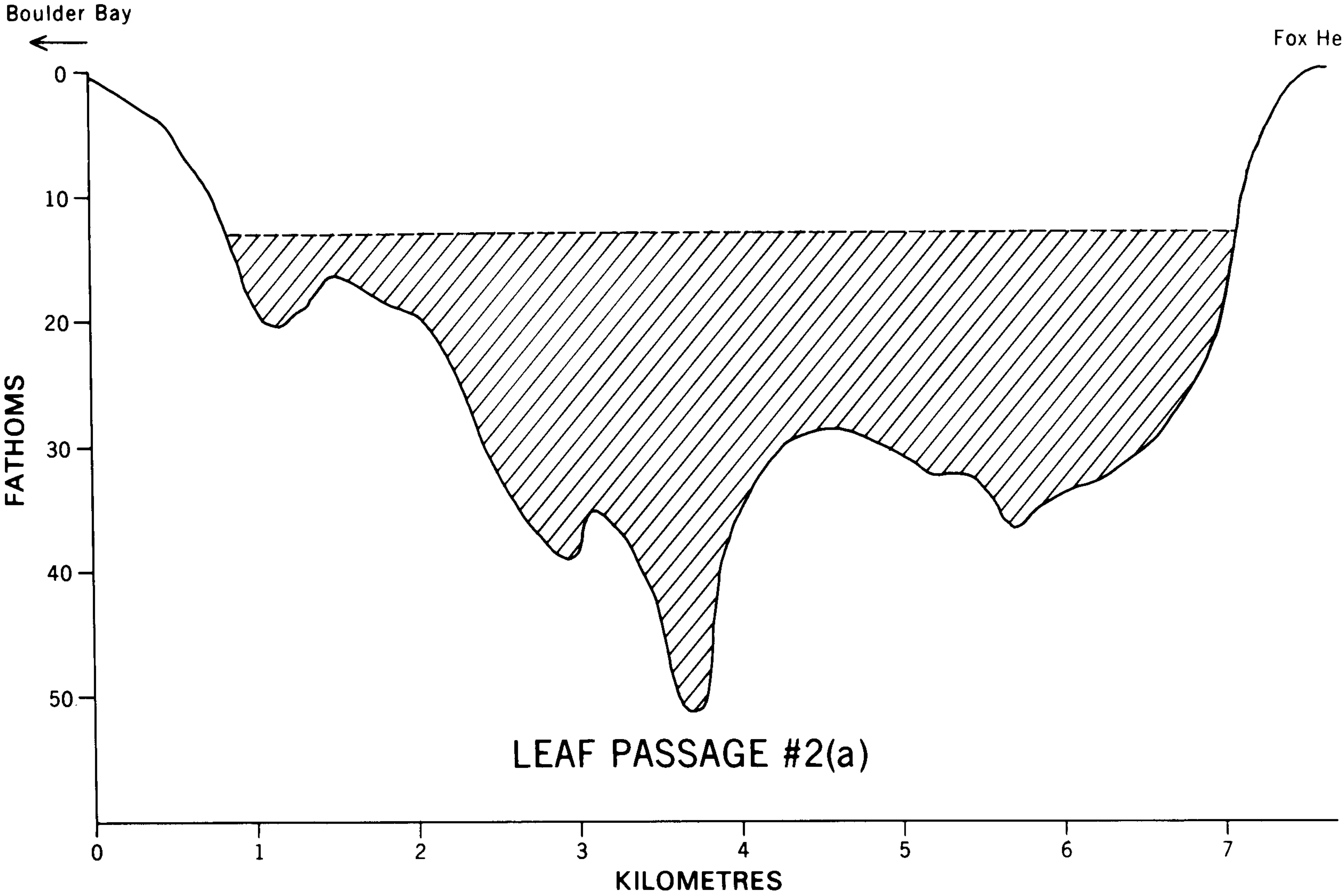
Boulder Bay
Fox Head
0
10
20
30
40
50
FATHOMS
LEAF PASSAGE #2(a)
0
1
2
3
4
5
6
7
KILOMETRES

Fig. 13(b)

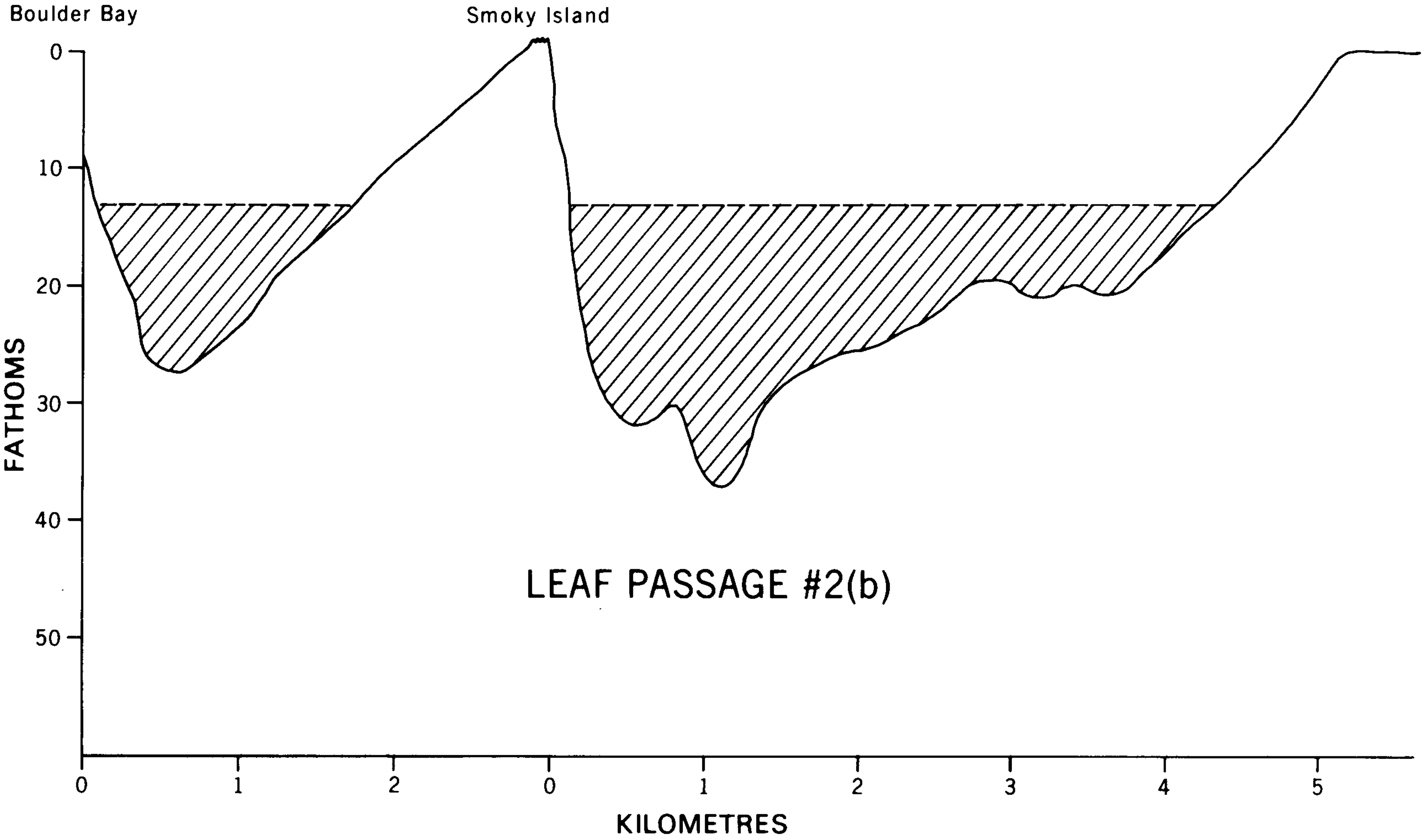
Boulder Bay
Smoky Island
0
10
20
30
40
50
FATHOMS
0
1
2
0
1
2
3
4
5
KILOMETRES
LEAF PASSAGE #2(b)

Fig. 13(c)

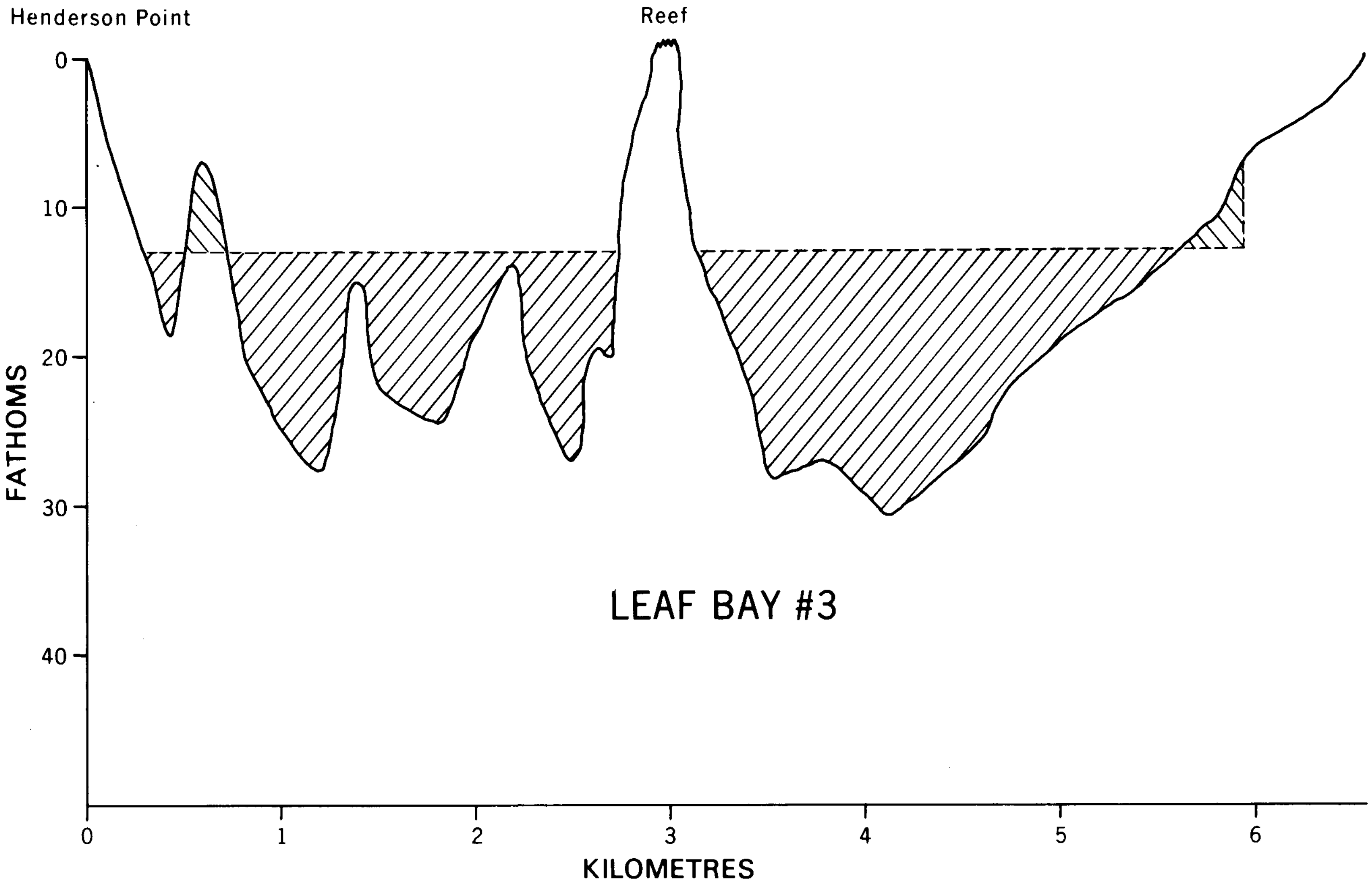
Henderson Point
Reef
0
10
20
30
40
FATHOMS
LEAF BAY #3
0
1
2
3
4
5
6
KILOMETRES

Fig. 13(d)

Further seaward in Leaf Passage the depths are not as great. A possible closure could extend obliquely from Boulder Bay to Fox Head, (Figure 12b), where 6.27 km of width are deeper than 13 fm while 6.3 km would be required to house the generating units; it could barely exploit the full power potential (Figure 13b). A second closure in the same area could be established in two portions using a reef as an anchor (Figure 12b). The depths would be less than over the previous section (Figure 13c) but only 6.0 km of width would be of a depth greater than 13 fm. Excavating could raise this width to at most 6.5 km.

The last project right out in Leaf Bay (Figure 12c) would yield the most energy. The dyke would have to be made up of three parts to accommodate all the necessary turbines. It provides 7.7 km of width of depth exceeding 13 fm and it could easily be increased to 8.1 km (Figure 13d). The shape of the closure might create problems. No soundings are available for the outer sections of Island Sound but if it is very shallow, there might occur appreciable differences of head between the northern and southern sections of the closure. Ice abrasion and ice accumulation might also act selectively on some portions of the closure to the detriment of the whole structure. If these possible difficulties do not materialize, this would be the ideal choice.

Only one closure seems possible in the Koksoak (Figure 14). The cross section (Figure 15) indicates that 1.5 km of width would be deeper than 13 fm. This could be brought up to 1.8 km without too much difficulty, but there would be almost

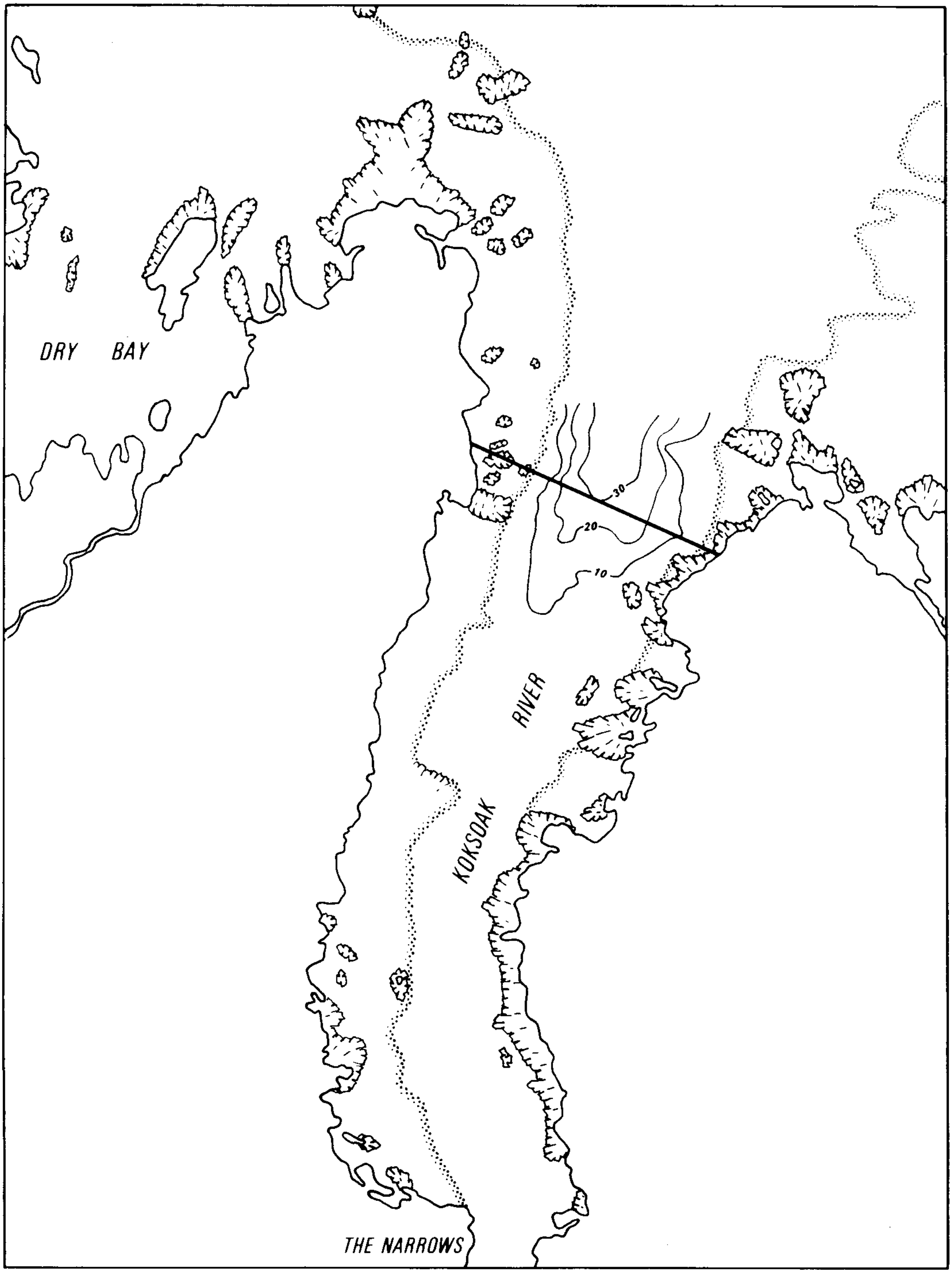

Fig. 14 Location of the closure in the Koksoak Basin.

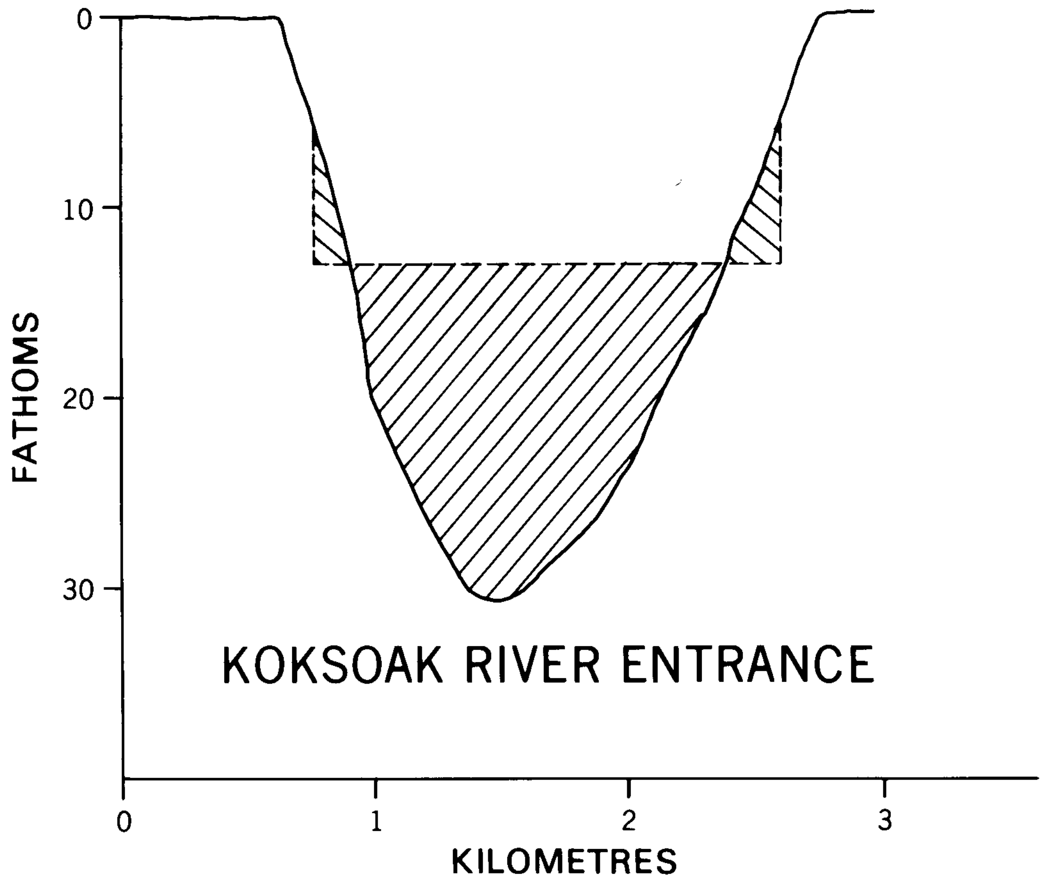

Fig. 15 The corresponding horizontal cross section in the Koksoak Basin.

no space for sluices. The dynamics of the water motion inside the estuary and especially beyond the Narrows will have to be carefully studied before any attempt is made at exploiting the tide in the Koksoak estuary.

We have no soundings available for the remaining basins. In False River (Figure 16) a closure 6.3 km in width could be thrown between (58°29'N,67°55'W) and (58°27'N,67°47'W), which seems pretty wide compared to the 2.0 km required for the machinery. Further inside the basin, the width could be reduced to 3.3 km between (58°25'N,67°52'W) and (58°24'N,67°48'W). In the Whale (Figure 16) a double dyke could be thrown on both sides of Big Island with lengths of 3.6 km and 3.0 km (over very shallow depths), the points joined being (58°25'N,67°40'W)-(58°24.5'N, 67°35'W) and (58°20'N,67°28'W)-(58°18'N,67°25'W), while in the George (Figure 17) closures of 7.8 km or 3.9 km suggest themselves between (58°47.9'N,66°12.5'W)-(58°49.8'N,66°07'W) and (58°45'N, 66°9.5'W)-(58°45.5'N,66°6.5'W).

No special map is available for Keglo Bay. In Abloviak Fiord (Figure 18), a closure of 0.8 km in width suggests itself between (59°29.5'N,65°20'W) and (59°29.9'N,65°20'W). Table 7 summarizes the information given in the preceding paragraphs. It also lists the volumes of rock to be excavated or filled. In the excavation, we assume that a swath 130 m in width has to be cleared. For the filling, we assume that the fill will take the shape of a trapezoid of cross-sectional area equal to $2h^2$ where h is the depth of fill.

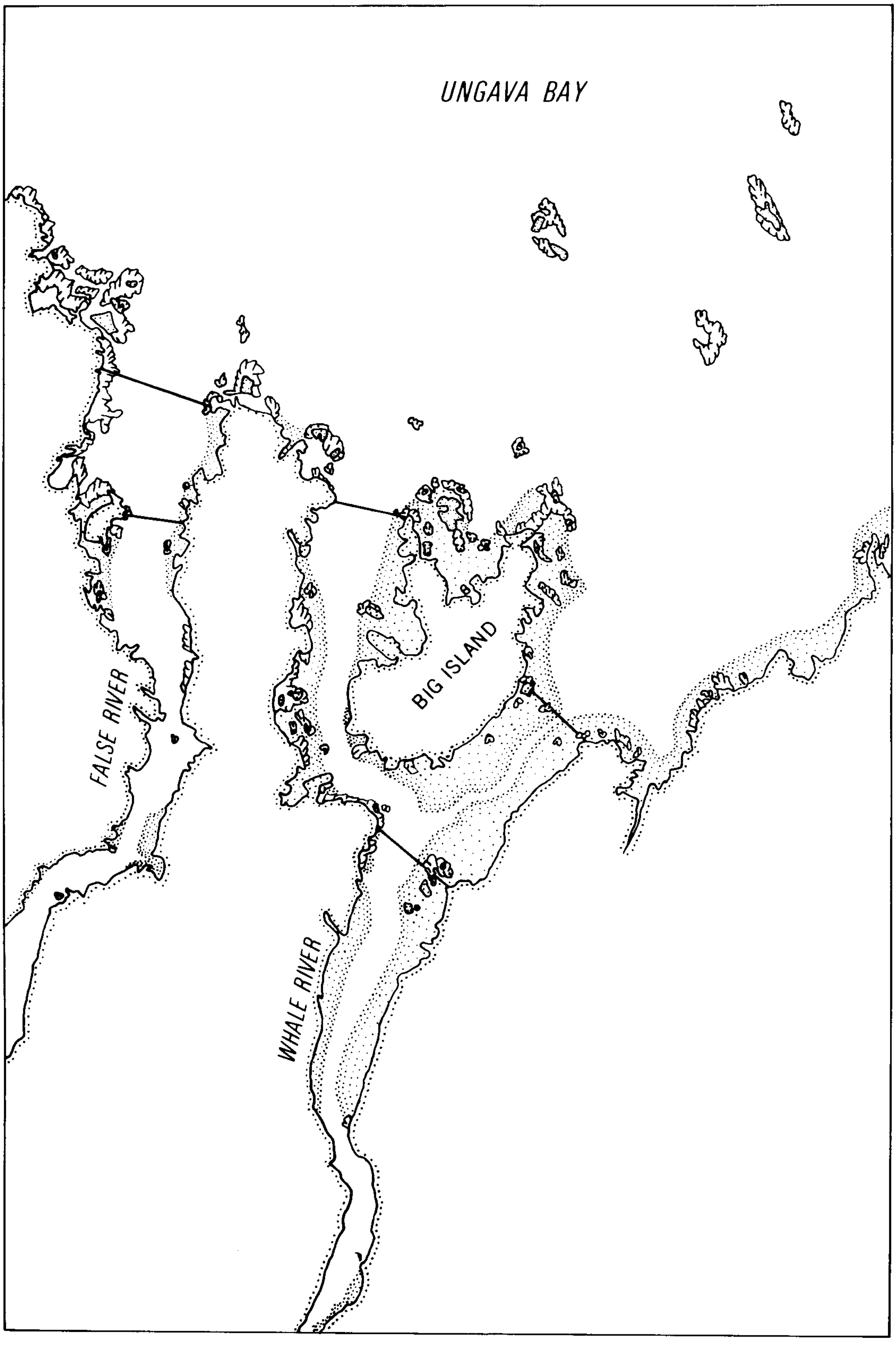

Fig. 16 Possible locations of the closures in the False River Basin and in the Whale Basin.

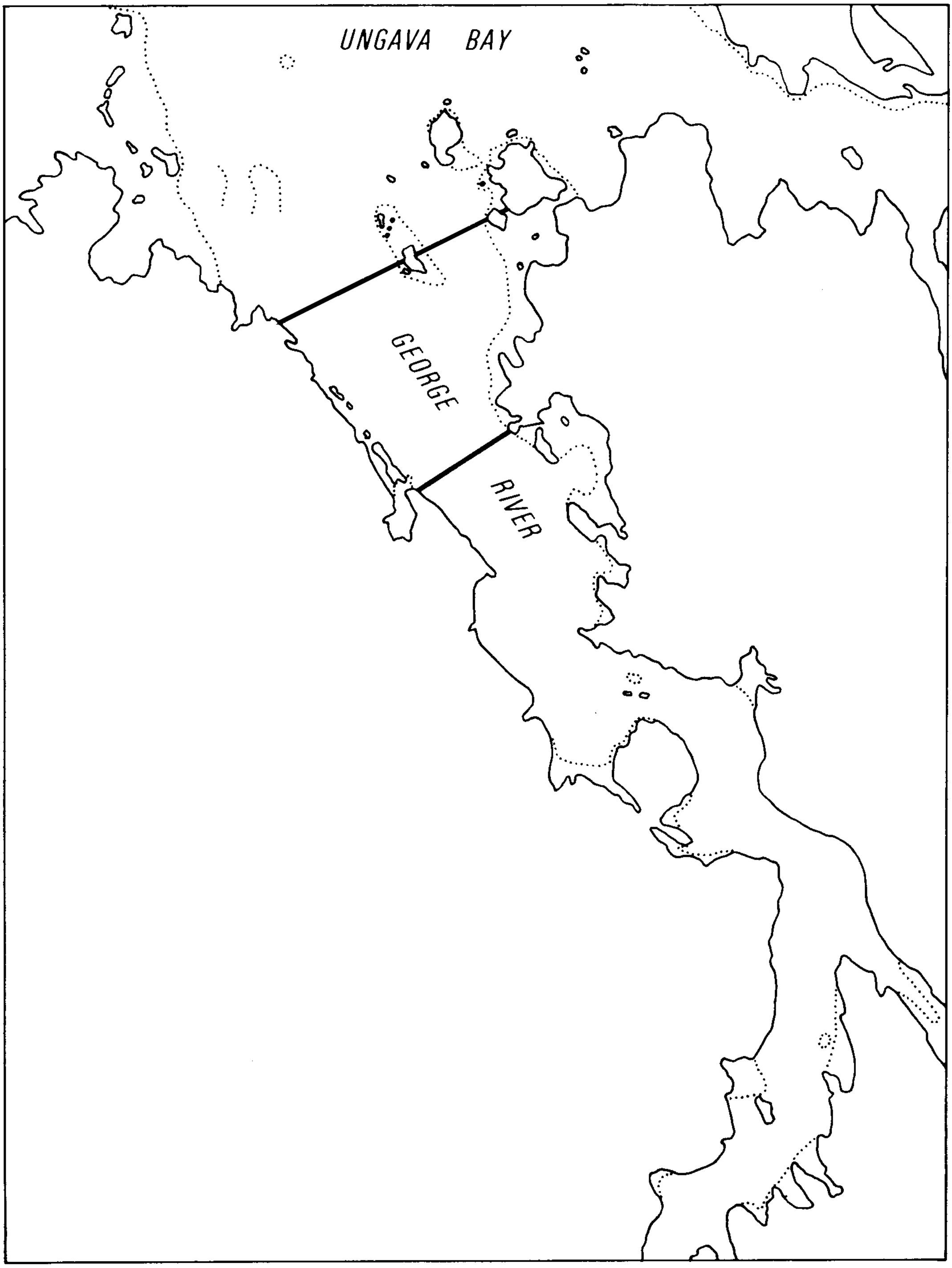

Fig. 17 Possible closures in the George Basin.

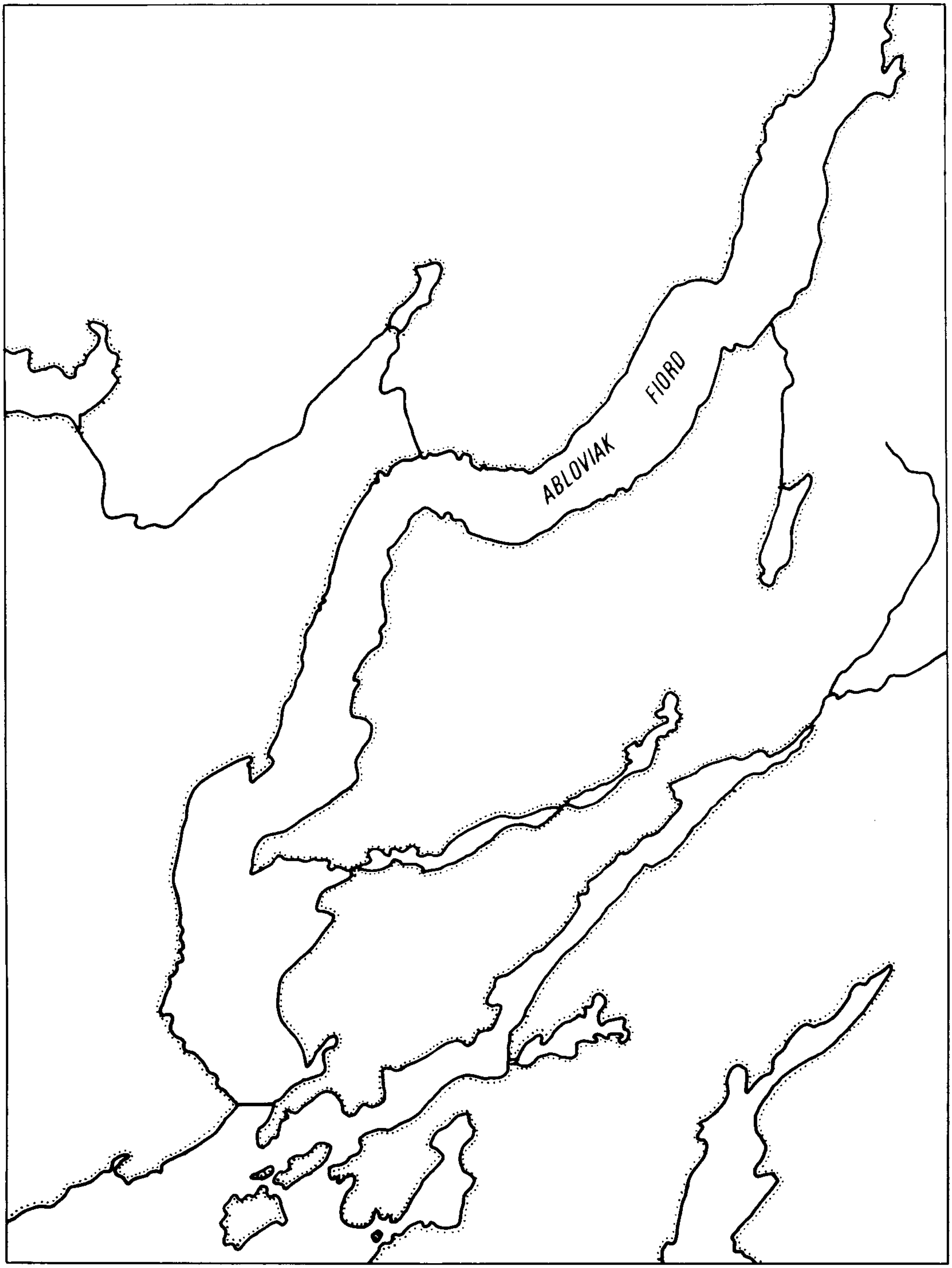

Fig. 18 Closure in Abloviak Fiord.

Table 7 Some features of the closures of the tidal basins around Ungava Bay

Basin	Length of closure	Additional dykes length	Width required for the turbines	Width of closure deeper than 13 fm	Volume of excavation	Volume of fill
	km	km	km	km	$\times 10^3 m^3$	$\times 10^6 m^3$
Payne (Fig. 10)						
1	8.1	3.3	3.2	4.3	0	.51
2	5.8	0.1	2.4	2.4	294.6	.14
3	4.6	0.5	1.8	2.2	0	1.19
Ikattok	9.0	0	1.2	-	-	-
Leaf (Fig. 12)						
1	6.5	0	4.4	5.0	90.3	11.61
2 a)	7.7	-	6.3	6.3	0	5.37
b)	8.5	-	6.3	6.0	0	4.17
3	11.2	0	7.1	7.7	439.8	1.79
Koksoak (Fig. 14)	3.0	0	1.6	1.5	366.1	1.45
False River (Fig. 16)						
1	6.3	0	2.0	-	-	-
2	3.3	0	2.0	-	-	-
Whale (Fig. 16)						
1	6.6	0	1.8	-	-	-
2	3.0	~ 1	1.8	-	-	-
George (Fig. 17)						
1	7.8	0	2.1	-	-	-
2	3.9	0	2.1	-	-	-
Keglo		-	.6	-	-	-
Abloviak Fiord (Fig. 18)	.8	0	.6	-	-	-

- Not available

4.4. The combined exploitation of a hydroelectric plant on a river and of a tidal power installation

A hydroelectric plant, provided its installed capacity exceeds its average power generating capacity, may meet peaks in demand on its own at the expense of its average performance. A tidal installation can only generate blocks of power at a time and intensity which are determined exclusively by the tide; it can provide neither base load nor dependable peak capacity. However, the combination of a river plant with a tidal installation of lesser capacity can meet a given requirement of base load and peaking, (Bernshtein, 1965). This implies an increase of the installed capacity of the river plant to the required maximum peak power to be supplied. We can express the situation quantitatively as follows. The demand D(t) consists of the fixed base load B and the added peak demand P(t), t indicates the time and (t) a dependance on time. Thus

$$D(t) = B + P(t) \tag{18}$$

Strictly speaking, B may not be a constant and may effectively vary from day to day. What equation 18 is trying to convey is that the base load B does not vary on an hourly basis while P(t) does. B and P(t) are based on forecasts and are to be treated as known quantities. During the course of one year, P(t) will reach an absolute maximum value P_o, which is also considered to be known. This demand D(t) has to be met by the power generated by the river plant R(t) and that of the tidal installation, T(t).

Thus

$$R(t) + T(t) = D(t) \tag{19}$$

T(t) varies between the limits

$$0 \leq T(t) \leq B \tag{20}$$

since there is a remote possibility that the tidal plant supplies its peak power at the instant of least demand. Equation 20 indicates that under no circumstances should the output of the tidal installation exceed the base load B required for the day. This output is also restricted by the installed capacity N_i. This restriction in turn imposes the limits

$$0 \leq R(t) \leq B + P_o \tag{21}$$

on R(t).

The installed capacity of the river plant must therefore meet the largest peak in demand in case the tidal plant fails to produce any power at that instant. If at the instant of least demand, the tidal installation produces the peak power N_i for which it has been designed, the values of N_i should be less than or equal to B, the base load on that day.

Equations 20 and 21 delineate the limits of installation and performance. However, the average value in time of equation 21 must be such that the average power outputs of the river plant and the tidal installation amount to $\overline{R}$ and $\overline{T}$ respectively, the mean power output determined by their physical characteristics which are given in Tables 3 and 4 for Ungava Bay. The plants must supply on the average, the energy which they are cut out to supply, neither more nor less:

$$\overline{R(t) + T(t)} = \overline{D(t)} \tag{22}$$

and

$$\overline{R(t) + T(t)} = \overline{R} + \overline{T} \tag{23}$$

where the bar denotes the average over time. In practice $\overline{T}$ is somewhat larger than the value quoted in Table 3 (Godin, 1969). $\overline{R}$ and $\overline{T}$ are known quantities since they are determined during the design of the plants.

$$\overline{D(t)} = B + \overline{P(t)}$$

is determined by the forecast of load demand which can be met by the combination of a tidal power plant and a river hydroelectric plant. The time average in equation 22 needs to be carried at most over 15 days for the tidal plant to yield a fair value of $\overline{T}$; for $\overline{R}$ the averaging has to be carried over at least one year.

In the design of the system, $\overline{R}$ and $\overline{T}$ can be estimated pretty accurately beforehand. The peak demand in the design, $B + P_o$, must be such that it can be met by the combination of R and T. This implies that in practice the combination will be expected to meet only partially the demand of the whole network. This also implies a large reservoir capacity; this condition is satisfied for all the rivers listed in Table 4. The installation of the river plant will duplicate appreciably that of the tidal plant. At the tidal plant, the installation will be N_i as given in Table 3. The actual output of the river plant at a given time will be given by equation 21 in the form

$$R(t) = D(t) - T(t)$$

The output of the river plant R(t) is determined by the demand D(t) and the tidal output T(t), since the output of the tidal plant is uncontrollable while R(t) is controllable.

The exploitation of such a combination requires a large installed capacity with low turbine utilization, but complete flexibility is insured. Also the energies of both the river and the tide will be fully utilized on the average (see equation 23) while the instantaneous demand (as designed) will always be met.

4.4.1 The joint exploitation of the tide in Leaf Basin and of the hydraulic energy of the Koksoak and George Rivers

The somewhat abstract considerations of the previous paragraph can be made less so by considering the joint exploitation of the tidal power in Leaf Basin (Project 3) and of the hydraulic power of the Koksoak and George Rivers. We use the forecast demand in 1980 for Québec to represent the power demand D(t). One interval covers April 3-April 18, 1980 (early spring) a period of relatively light demand, while the second covers

December 4-December 18, 1980 (winter), an interval of heavy demand (Anon., 1969).

The combined power capacity of the Koksoak and George Rivers is some 10,200 MW, while the Leaf Basin tidal plant can supply 2,300 MW on the average, in the form of bursts of power which can reach 10,500 MW on rare occasions.

Figures 19 and 20 show in lines of different thickness, the demand D(t), the river output R(t) and the tidal output T(t) for the two seasons. The sum of R and T is devised to meet the demand D at all times. We also show in the same diagram the predicted tide in Leaf Basin.

We are faced in the early spring by the strong equinoctial tides which induce rather extreme variations in the tidal power (Figure 19). The mean power output of the tidal plant over the 374 hours of operation amounts to 2,985 MW, well above the expected mean output of 2,300 MW. The average output from the hydro plants is 9,350 MW; the extreme hydro output is 15,883 MW which has to be supplied around hour 274 when a peak in demand occurs with the tidal plant being shut off. Since the average hydro capacity is 10,200 MW, water has been saved over this interval equivalent to an output of 850 MW over 15 days. The sum $\overline{R} + \overline{T} = 12,335$ MW is slightly smaller than the mean combined capacity of 12,500 MW because of the reduced demand. It may be noted that part of the hydro output could have been supplied by other sources of power that could have provided a base load totalling 1.367×10^6 MW-hr over the 15 days of operation. This base load would have had to supply a maximum of about

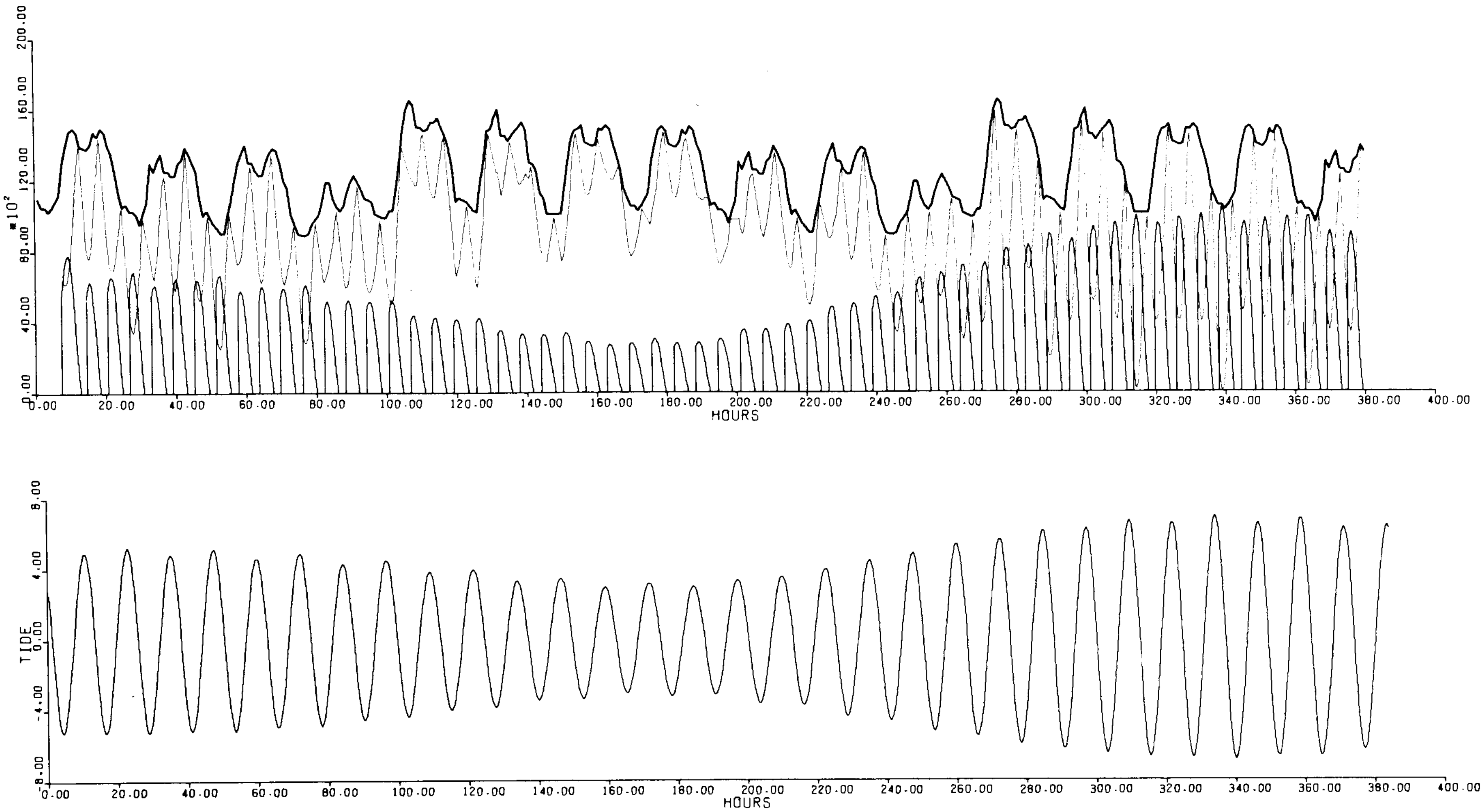

Fig. 19 The supply of the hypothetical demand D for Québec in 1980 during early spring. The upper diagram shows the demand D, the hydro output R and the tidal output T in lines of different thicknesses. The lower diagram shows the predicted tides.

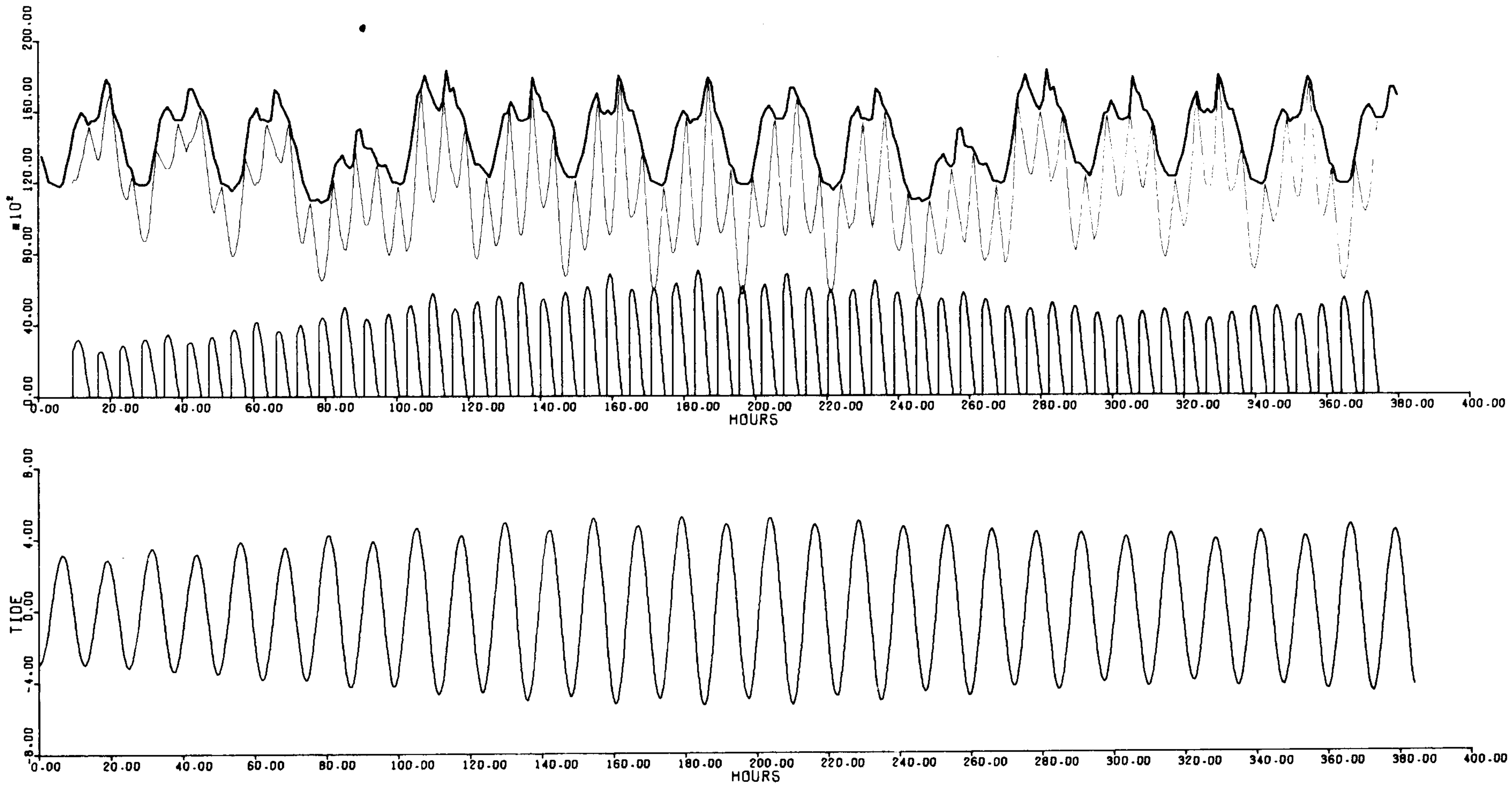

Fig. 20 The same situation during early winter, an interval of heavy demand and more even tides.

7,000 MW between hrs 160 and 200, covering the equinoctial neap tide, with adjustment in this base load being necessary about every 20 hrs; the hydro plants would then be used exclusively for peaking.

Figure 20 shows the winter situation. The tide is more even during the interval considered so that the tidal power fluctuates between narrower limits. The mean tidal output is 2,459 MW, much closer to the 2,300 MW we expect out of it, while its largest peak is 7,092 MW, well below the 10,500 MW which occurred during the spring season. The demand is heavier though and the hydro plants have to supply a mean capacity of 11,986 MW with a peak output of 17,668 MW at hr 330 when once again the tidal plant fails to operate at an instant of peak demand.

Figures 19 and 20 help illustrate the ideas developed in the previous paragraph. It is now evident that in order to meet the demand at all times, it is necessary to have large installations on both the river and tidal plants that exceed their average capacity by a large factor. On the other hand, the potential energy of the water is utilized at all times with near peak efficiency, since there is no need in such a type of exploitation to have recourse to any form of energy storage, like pumped storage, which implies considerable energy losses. In addition, pumped storage would lead to great practical difficulties in the near-arctic climate which prevails in the Ungava area.

5. Environmental consequences

In the event that the scheme proposed for the development of Ungava Bay and the rivers of its hinterland is carried out, a serious study of the environmental consequences will have to be undertaken well in advance. The immediate transformations implied by the scheme are obvious and include: a) the discharge of the rivers used for power generation will become regulated, b) vast water reservoirs will be created, c) some land will be permanently flooded while other areas will be irregularly wetted depending on the power demand, d) long dykes will effectively isolate some estuaries and bays from the open ocean, e) penetration roads will have to be slashed through the wilderness and f) transient centres of population will be established at the construction sites with some remote possibility of permanent settlements in the Ungava. The long range repercussions of these transformations on the local climate, the isostatic balance, soil stability, water table, advection of nutrients, erosion of banks, forest and plant cover, and the animal and fish life are not easy to predict. Only engineering, economic and political considerations would have prevailed a little while ago and the secondary effects just mentioned would have been generally overlooked. Lately our sense of responsibility has expanded with the sudden realization that however powerful we feel in reshaping the face of the earth, the earth which we thought inert and subservient could hit back at us savagely whenever we had hurt it inadvertently. With this in mind we should not venture into the Ungava without having weighed fully all the possible consequences.

6. Prospects of development

The load forecast in 1985 for Québec province is 27,000 MW. In 1967 its generating capacity was 10,957 MW, 94.7% of which was hydro, and with the incorporation of the Manicouagan and Outardes power plants and the output of Churchill Falls in Newfoundland, all hydro projects, the capacity will be raised to 16,000 MW by 1978. The James Bay development should add an extra capacity of 10,000 MW by 1985, raising the total generating capacity to some 26,000 MW (Anon., 1969). These forecasts are based on an assumed load growth of 7.7% per year. Due to local circumstances the economic growth of the province has slowed appreciably since 1970 and the actual demand in 1985 might not reach the value anticipated. The prospects for the development of the power resources of Ungava Bay and its hinterland to meet the future needs of Québec itself are, therefore, rather dim.

On a larger scale, the power needs of eastern North America are still increasing steeply and the power potential of the Ungava could become attractive if means were found to develop it economically. The primary obstacle is the great distances involved, for example the tidal plant on Leaf Basin would be 1,500 km from Montréal. The cost of the transportation of large blocks of power at high voltage using conventional transmission lines and the losses involved appear prohibitive. New and more revolutionary methods of energy transmission involving for example the transformation of electric energy into microwaves, will have to be devised before a serious attempt is made to develop the Ungava Bay power resources. Gregory (1973) has suggested recently the use of the electrical energy in situ to produce hydrogen gas which would then be piped to the centers of consumption. This would imply a loss of energy of approximately 60% but the costs and difficulties of constructing a transmission line would be replaced by those of a simple pipeline which would require much less land use and present fewer hazards. A more immediate obstacle to such an undertaking is the lack of land transportation to the sites shown in Figure 1. A railroad, the Québec North Shore and Labrador, pushes from Seven Islands as far north as Schefferville, in the center of the Québec northland; this railroad has already proven of value in the construction of the Churchill Falls project. In order to develop the Ungava, two branch roads should extend from Schefferville, one towards the George River, the other towards Eaton Canyon on the Kaniapiskau River and then along the river as far as Fort Chimo. From Fort Chimo, a side road could be built towards Leaf Basin and the Payne River. The two main roads would be about 500 km in length while the extension to Payne River would add 200 km. Once a road system is established, the exploitation of the Ungava could become less hypothetical.

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