CANADA

CAUSEWAY INVESTIGATION NORTHUMBERLAND STRAIT

REPORT ON TIDAL SURVEY 1958

by
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PREFACE

The tidal survey of Northumberland Strait, between Prince Edward Island and the mainland, was carried out between May and mid-October of 1958 by the Tidal and Inland Water Levels Section of the Canadian Hydrographic Service.

The motor-vessel "Theta" was chartered for the survey to lay automatic current meters with which to establish a network of stations where continuous observations could be obtained for periods of at least 15 days and in order that current observations could be obtained for 24-hour periods from the ship itself when anchored at a great many additional stations throughout the Strait. These observations were supplemented by others taken by the Consulting Engineers, C. B. Joint Venture, for 13-hour periods, mainly in the vicinity of the proposed site of the causeway.

The problems of mooring and safeguarding the automatic current meters were solved with the aid of cables, buoys and other equipment loaned by the Marine Agent of the Department of Transport at Charlottetown, and valuable advice and assistance were given by his staff.

Tide gauges were installed at 24 sites, these being in addition to those already in operation at Auld Cove in the Strait of Canso, at Pictou, Nova Scotia, and at Charlottetown and West Point, Prince Edward Island. The necessary huts and stilling wells were provided by district engineers of the Federal Department of Public Works at Charlottetown, Halifax and Saint John.

At three sites - North Point and Canoe Cove, Prince Edward Island, and Cape Cliff, Nova Scotia - where there were no suitable wharves for the installation of float-operated gauges, distant-recording pressure gauges were used. These were designed by the National Research Council of Canada for use where lack of facilities or difficulties of terrain prevent the installation of float-operated gauges, such as in the Bay of Fundy, Ungava Bay and the Arctic.

Oceanographical observations obtained during the survey were analysed by the Atlantic Oceanographical Group, Fisheries Research Board of Canada, and their conclusions have been embodied in this report. Meteorological information, necessary for the investigation of the storm surges which occurred during the winter of 1958-59, was supplied by the Department of Transport.

The survey was planned and carried out under the direction of Commander W. I. Farquharson, Officer in Charge, Tidal Survey. Mr. C. M. Cross was in charge of field work for the last six weeks of the survey. The principal assistants operating in the ship were Messrs. W. H. Henry and D. Dobson, supported by a staff of technicians and students. A smaller party under Mr. R. C. DesLauriers operated in the field for part of the season but was mainly engaged in processing and analysing the records obtained from the automatic current meters.

Throughout the survey, close contact was maintained with the staff of C. B. Joint Venture and with Dr. C. N. Forward of the Geographical Branch, Department of Mines and Technical Surveys.

N. G. Gray
Dominion Hydrographer

Ottawa, February 15, 1959.

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CAUSEWAY INVESTIGATION NORTHUMBERLAND STRAIT
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FOREWORD

The major objective of the survey was to determine how the construction of a completely closed causeway, between Cape Tormentine, New Brunswick, and Port Borden, Prince Edward Island, would affect the following:

The high-water and low-water levels throughout the Strait and the range of the tide in the principal harbours. Such information is necessary to assess the affects of a causeway as regards damage to foreshore property, increased siltation and the need to raise wharves and other harbour works, or deepen harbours and approach channels.

The levels of the water upon the two sides of a completed causeway. This information is necessary, because the creation of a head of water would, to a great extent, determine the flow to be contended with in the final stages of closure.

The construction of a causeway would transform the Strait into two separate gulfs, and the propagation of the tide would be changed considerably. This change would affect the times when high water occurs and the ranges of the tide, in various parts of the Strait. These in turn would lead to the creation of differences in level on the two sides of the causeway and to changes in the high- and low-water elevations over the greater part of the Strait. There is also the possibility that a causeway would influence, locally, the non-periodical fluctuations in sea level which are generated by meteorological disturbances. These could temporarily increase the head of water at the causeway, and it is possible that, in some harbours, these non-periodical fluctuations might become greater in amplitude than under present conditions.

The investigation into the tidal changes was carried out by the Liverpool Observatory and Tidal Institute, England. For this investigation the Institute was supplied with data on existing tidal conditions, consisting of the harmonic constants of the constituents of the tides and tidal streams at more than one hundred sites on the shores of, and in, the Strait. Their conclusions as to tidal conditions after the construction of a causeway are given mainly in a similar form.

The non-periodical fluctuations in sea level are entirely distinct from the tides and tidal streams, the former being controlled by meteorological, and the latter by astronomical, conditions. The non-periodical fluctuations fall into three groups, according to the period covered by each fluctuation. Seiches are the most rapid fluctuations, with periods of from a few minutes to about an hour, and, in the area under investigation, do not exceed about 2 feet in range. Storm surges alternately raise and lower sea level by amounts of as much as 4 feet or more, in a period between successive high levels of one to one and a half days. They may continue for as long as a week, or ten days, if there are repeated gales and marked changes in barometric pressure. Seiches are more likely to occur in summer, usually with the abrupt changes associated with thunderstorms, while surges are generated by the severe gales most frequent in other seasons. Both will affect the head of water at a causeway, should there be appreciable differences in their phase or range on the two sides. Secular changes in sea level, the third group, are associated with long-term climatic changes and are not expected to amount to more than one foot per century. They can have no affect upon the head of water at a causeway, but a long-continued rise in sea level would mean that the sea reached heights, now regarded as exceptional with greater frequency.

In order to forecast the effects of the proposed causeway upon these fluctuations, it is essential, as with the tides, to be fully acquainted with their behaviour under existing conditions. The responses of the sea to the periodical changes in astronomical conditions can be adequately determined from a relatively short series of continuous observations at a network of stations. The most adverse effects of changes in meteorological conditions are, however, comparatively rare and in order to investigate them thoroughly it is necessary to have a network of stations in continuous operation over a period of years. Such a network has only been in operation since the commencement of this survey and in consequence any immediate conclusions as regards the non-periodical fluctuations must be largely speculative.

The non-periodical, horizontal movements of the water, referred to in this report as 'residual currents', fluctuate, with changes in meteorological conditions, to a much greater degree than do the vertical movements. In consequence, a survey of short duration cannot lead to firm conclusions in this respect.

1. OBSERVATION, ANALYSIS AND COMPUTATION OF TIDES AND TIDAL STREAMS

In every sea the observed tides are the resultant of a semidiurnal component, with two high waters and two low waters in the course of a day, and a diurnal component with only one high water and one low water in that period. The observed tidal streams are similarly the resultant of semidiurnal and diurnal components.

Both components consist of a group of constituents, each of which represents the response to an individual change in the astronomical tide-raising forces. Any changes in the depth, shape or size of any gulf, strait or bay will have different effects upon the propagation of the two components and, with either components, may affect some of the constituents to a greater degree than others. In the case of Northumberland Strait, it has been shown that the changes in the diurnal component will be small and affect all the diurnal constituents to the same degree. In consequence it is sufficient to determine the changes which will occur in the principal diurnal constituent K_1 and to assume similar changes in the other diurnal constituents. With the semidiurnal component the changes will be greater and, in some parts of the Strait, the changes in the solar constituents will not be the same as those in the lunar constituents. For this reason it has been necessary to determine separately, the changes in the principal lunar semidiurnal constituent M_2, and those in the principal solar semidiurnal constituent S_2. It is then assumed that the other lunar semidiurnal constituents will be affected to the same degree as M_2 and the other solar semidiurnal constituents to the same degree as S_2.

At any place, provided that there are no alterations to the underwater topography of the strait or gulf in which it is situated, the lag, and the amplitude of the response, of the sea to a particular harmonic constituent of the tide-raising forces is constant. These constants are the phase lag "g" and the amplitude "H" of the response. They differ for each constituent and for any constituent change from place to place, the changes in "H" indicating an increase or decrease in amplitude and range, and the changes in "g" indicating that high water occurs earlier or later. Thus "g", the phase lag expressed as an angle, may also be referred to as a high-water angle.

The high-water angles and the amplitudes of the various semidiurnal and diurnal constituents, throughout the Strait, will all be affected by the construction of a causeway.

Observation and Analysis

The Tidal Institute, for its final investigation into the changes in the tides which would be brought about by construction of a causeway, were provided with the harmonic constants of the principal constituents of the tides and tidal streams , as follows:

Tides: At twenty four gauges established at sites along the shores of the Strait, for periods of five to twelve weeks during the summer of 1958, and at sixteen gauges installed inside harbours for various periods during earlier years. The sites extend from St. Peter's Bay and Tignish on the north coast of Prince Edward Island, along the east, the south and west coasts of the Island. On the shores of the mainland they extend from Cheticamp Island, Nova Scotia, to Point Sapin, New Brunswick.

In addition to these which were computed by the Hydrographic Service, harmonic constants at Charlottetown from many years' observations, and at Pictou, from one year's observations, had previously been determined by the Institute. These harmonic constants are given in Table 1a, page 9. The positions of these tide gauges are given in Figures 1a and 1b, pages 13 and 14.

Tidal Streams: At nine stations where continuous observations were obtained for periods of 15 days or more, from six stations where the observations were obtained for one week or longer, from fifty-four stations where observations were taken for 24 hours and from sixteen stations where the Consulting Engineers took them for 13 hours. At fifty of these stations the observations were obtained at two or more different depths. The section lines, along which these observations were obtained, extended throughout the Strait from between East Point, Prince Edward Island, and Grey Point, Cape Breton Island, to between North Point, Prince Edward Island, and Escumiac Point, New Brunswick. These harmonic constants are given in Table 1b, pages 10 - 12.

The positions of the tidal stream stations are given in Figures 1a and 1b, pages 13 and 14.

Computation

The Tidal Institute, from the harmonic constants of the observed tides and tidal streams in the eastern and western entrances, and from the known breadths and depths of the Strait at successive section lines and the distances between those section lines, computed the tides and the tidal streams to be expected at those section lines. The accuracy of the method, used to obtain these computed values, was then established through comparison between the computed constants and those derived directly from observations.

Being satisfied on this point, the Institute was then in a position, again commencing with the harmonic constants of the observed tides and tidal streams in the eastern and western entrances, to compute the tides to be expected at the various section lines after the construction of a causeway. The details of these computations and the conclusions reached by the Institute are given in Appendices B_1 and B_2.

TABLE 1a

HARMONIC CONSTANTS OF THE TIDE

Place	M_2		S_2		K_2		N_2		K_1		O_1		P_1		M_4		MS_4	
	g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H
Prince Edward Island																		
St. Peter's Bay	181	0.42	244	0.15	244	0.04	172	0.13	258	0.47	230	0.49	258	0.16	208	0.01	086	0.01
Naufrage	193	0.58	248	0.19	248	0.05	175	0.13	257	0.62	223	0.52	257	0.21	144	0.04	233	0.01
North Lake	246	0.52	302	0.13	302	0.03	229	0.13	286	0.41	251	0.48	286	0.14	029	0.01	139	0.02
Souris	253	1.15	304	0.29	304	0.08	226	0.28	255	0.60	220	0.57	255	0.20	297	0.04	068	0.02
Georgetown	260	1.29	317	0.37	317	0.10	217	0.28	261	0.55	226	0.54	261	0.18	309	0.04	358	0.04
Graham Pond	260	1.25	318	0.33	318	0.09	220	0.27	254	0.57	221	0.59	254	0.19	286	0.05	107	0.01
Murray Harbour	277	1.37	339	0.36	339	0.10	254	0.29	268	0.56	241	0.58	268	0.19	009	0.03	142	0.04
Wood Island	288	1.79	349	0.38	349	0.10	251	0.40	260	0.66	233	0.70	260	0.22	270	0.04	321	0.02
Prim Point	300	2.30	015	0.51	015	0.14	267	0.51	264	0.81	233	0.82	264	0.27	065	0.05	191	0.04
Charlottetown	307	2.40	011	0.61	011	0.19	279	0.50	267	0.82	240	0.74	271	0.26	068	0.06	159	0.04
Canoe Cove	310	2.23	020	0.54	020	0.15	274	0.48	265	0.81	233	0.76	265	0.27	093	0.06	144	0.05
Victoria	311	2.37	022	0.66	022	0.18	275	0.48	262	0.81	233	0.73	262	0.27	121	0.06	218	0.07
Borden	316	1.92	026	0.47	026	0.13	279	0.47	262	0.88	236	0.71	262	0.29	185	0.07	212	0.04
Summerside	322	1.76	043	0.36	043	0.10	296	0.39	267	0.78	233	0.76	267	0.26	240	0.05	350	0.03
Cape Egmont	324	0.76	066	0.19	066	0.05	278	0.15	270	0.82	230	0.73	270	0.27	227	0.07	355	0.04
West Point	004	0.40	098	0.20	098	0.06	330	0.04	269	0.82	230	0.72	269	0.28	261	0.05	007	0.05
Miminegash	119	0.61	182	0.21	182	0.05	114	0.16	246	0.60	224	0.60	246	0.20	009	0.02	195	0.02
North Point	128	0.72	186	0.22	186	0.06	088	0.18	244	0.54	211	0.48	244	0.18	168	0.03	263	0.02
Tignish	129	0.68	182	0.16	182	0.04	110	0.15	250	0.64	221	0.55	250	0.21	100	0.03	185	0.02
Nova Scotia																		
Cheticamp Island	250	0.62	294	0.19	294	0.05	248	0.16	262	0.45	235	0.50	262	0.15	255	0.01	124	0.02
Broad Cove	254	0.70	294	0.18	294	0.05	231	0.20	267	0.53	239	0.56	267	0.18	273	0.03	043	0.03
Port Hood	267	0.90	305	0.25	305	0.07	232	0.21	268	0.52	239	0.51	268	0.17	347	0.02	073	--
Auld Cove	275	0.94	330	0.29	330	0.07	232	0.27	282	0.54	238	0.53	282	0.19	317	0.04	048	0.03
Ballantyne's Cove	267	1.00	312	0.25	312	0.07	240	0.20	263	0.57	229	0.58	263	0.19	280	0.04	070	0.03
Arisaig	276	1.19	322	0.29	322	0.08	256	0.27	261	0.63	229	0.64	261	0.21	310	0.06	036	0.03
Merigomish	286	1.35	349	0.29	349	0.08	276	0.29	270	0.60	241	0.55	270	0.20	025	0.04	210	0.02
Pictou	295	1.28	348	0.36	001	0.12	270	0.33	271	0.68	246	0.55	256	0.21	319	0.03	090	0.01
Pictou Island	281	1.45	345	0.37	345	0.08	238	0.38	260	0.60	230	0.61	260	0.20	279	0.06	134	0.06
Caribou Harbour	292	1.50	350	0.29	350	0.08	267	0.30	276	0.61	247	0.59	276	0.20	354	0.02	077	0.02
Skinner's Cove	303	1.83	016	0.39	016	0.11	260	0.38	268	0.70	239	0.71	268	0.23	022	0.05	078	0.02
Malagash	309	2.20	013	0.47	013	0.13	279	0.53	269	0.72	242	0.68	269	0.24	057	0.04	222	0.02
Cape Cliff	311	2.16	024	0.39	024	0.10	275	0.60	267	0.78	238	0.76	267	0.26	042	0.05	232	0.04
Pugwash	319	2.34	030	0.56	030	0.15	301	0.47	268	0.79	239	0.77	268	0.26	051	0.04	126	0.04
Tidnish Head	311	2.40	024	0.53	024	0.14	274	0.55	267	0.83	236	0.80	267	0.28	126	0.07	175	0.05
New Brunswick																		
Port Elgin	324	2.37	045	0.55	045	0.15	293	0.54	278	0.84	247	0.83	278	0.28	197	0.25	272	0.15
Tormentine	310	1.92	033	0.48	033	0.13	264	0.49	263	0.74	234	0.71	263	0.25	131	0.06	190	0.03
Cape Bald	302	0.81	034	0.16	034	0.05	254	0.18	252	0.81	230	0.73	252	0.27	275	0.04	031	0.03
Shediac	301	0.65	032	0.13	032	0.04	261	0.15	252	0.84	235	0.73	252	0.28	292	0.07	019	0.06
Caisse Point	296	0.52	029	0.14	029	0.04	247	0.10	251	0.75	224	0.75	251	0.25	253	0.05	357	0.04
Crossman Point	287	0.22	090	0.10	090	0.03	209	0.09	255	0.77	228	0.69	255	0.26	265	0.07	072	0.05
Richibucto Harbour	144	0.40	169	0.11	169	0.03	129	0.10	245	0.73	215	0.65	245	0.24	196	0.03	242	0.02
Richibucto Bar	150	0.45	180	0.13	180	0.03	144	0.15	247	0.68	224	0.62	247	0.23	179	0.01	358	0.01
Point Sapin	131	0.64	169	0.16	169	0.04	124	0.17	239	0.69	216	0.66	239	0.23	130	0.02	--	--

TABLE 1b

HARMONIC CONSTANTS OF THE TIDAL STREAMS

		M_2		S_2		K_2		N_2		K_1		O_1		P_1		M_4		MS_4	
Station	Meter	g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H
A-1	P.W.	356	1.10	081	0.32					237	0.11	202	0.09						
A-2	G	015	0.79	100	0.22					036	0.16	356	0.12						
A-2	E	009	0.27	094	0.08					281	0.10	241	0.08						
A-3	G	014	0.23	099	0.08					325	0.17	285	0.14						
A-3	E	359	0.24	084	0.07					274	0.05	025	0.04						
A-4	G	014	0.36	099	0.11					332	0.13	045	0.11						
A-4	E	018	0.20	103	0.06	110	.22			005	0.08	325	0.06	046	.29	359	.07		
AB-1	P.W.	020	0.99	~~105~~	~~0.29~~	110	0.06	040	0.23	~~040~~	~~0.09~~	~~360~~	~~0.07~~	046	0.10	027	0.03	069	0.07
AB-2	G	024	0.44	105	0.15					345	0.22	305	0.17						
AB-2	E	017	0.36	102	0.11					308	0.05	268	0.04						
AB-3	G	041	0.16	126	0.04					043	0.34	003	0.26						
AB-3	E	026	0.30	111	0.10					087	0.07	047	0.06						
AB-4	G	003	0.30	088	0.12					323	0.17	283	0.13						
AB-4	E	024	0.20	109	0.06	99	.15			230	0.05	190	0.03	348	.10				
B-1	P.W.	016	0.40	~~101~~	~~0.12~~	099	0.04	330	0.06	~~355~~	~~0.24~~	330	0.19	348	0.03	178	0.01	113	0.03
B-2	G	040	0.35	125	0.10					358	0.34	318	0.27						
B-2	E	338	0.41	063	0.11					307	0.07	267	0.05						
B-3	G	047	0.78	132	0.23					001	0.19	321	0.15						
B-3	E	034	0.30	119	0.08					001	0.13	321	0.11						
B-4	G	033	0.25	118	0.06					041	0.08	001	0.07						
B-4	E	046	0.24	131	0.07					334	0.18	294	0.16						
B-5	G	014	0.57	045	0.16					078	0.12	038	0.10						
B-5	E	043	0.14	128	0.04					321	0.13	281	0.10						
C-1	G	041	1.14	126	0.33					006	0.15	341	0.12						
C-1	E	051	0.87	136	0.24					328	0.27	303	0.21						
C-2	G	047	0.43	132	0.13					332	0.06	307	0.05						
C-2	E	022	0.43	107	0.12					290	0.06	265	0.05						
C-3	G	037	0.38	122	0.11					357	0.11	342	0.08						
C-3	E	029	0.31	114	0.09					347	0.13	322	0.09						
C-4	G	005	0.15	090	0.04					040	0.08	000	0.06						
C-4	E	033	0.07	118	0.02					015	0.05	335	0.04						
C-5	G	052	0.34	137	0.10					345	0.09	320	0.07						
C-5	E	022	0.27	107	0.08					054	0.07	029	0.06						
C-6	G	042	0.47	127	0.14					024	0.32	359	0.26						
C-6	E	015	0.33	100	0.10					330	0.12	305	0.10						
C-7	G	055	0.57	140	0.17					212	0.21	187	0.17						
C-7	E	037	0.51	122	0.15						0		0						
D-1	G	048	1.00	123	0.30					023	0.26	013	0.20						
D-1	E	014	0.71	089	0.22					324	0.05	304	0.04						
D-2	G	036	1.28	111	0.48					317	0.28	297	0.22						
D-2	E	036	0.64	111	0.21					358	0.16	338	0.13						
D-3	G	009	1.00	084	0.34					332	0.04	312	0.03						
D-3	E	029	0.72	104	0.22					000	0.20	340	0.17						
E-1	G	051	1.39	126	0.42					341	0.50	321	0.41						
E-1	E	047	0.92	122	0.27					339	0.21	319	0.17						
E-2	G	070	1.30	145	0.40					336	0.57	316	0.46						
E-2	E	057	0.67	132	0.20					348	0.35	328	0.28						
b		068	1.13	142	0.33	142	0.04	035	0.30	359	0.23	305	0.15	359	0.07	268	0.04	076	0.02
E-3	G	064	0.66	139	0.20					326	0.24	306	0.20						
E-3	E	013	0.55	088	0.17					008	0.06	348	0.05						
C.E. Char.		040	0.72	115	0.21														
C.E. Hills.		052	1.54	127	0.46	165				151	.05								
F-1	P.W.	088	0.69	~~163~~	0.20	165	0.06	077	0.19	~~345~~	~~0.14~~	330	0.11	151	0.05	279	0.06	055	0.02
F-2	G	053	0.56	128	0.16					019	0.10	004	0.08						
F-2	E	033	0.58	108	0.16					064	0.12	049	0.10						
F-3	G	086	0.67	161	0.20					044	0.57	029	0.46						
F-3	E	036	0.58	111	0.16					120	1.47	108	1.19						
F-4	G	069	0.66	144	0.20					274	0.11	259	0.08						
F-4	E	065	0.34	140	0.10					145	0.23	130	0.19						
FG-1	G	099	0.43	174	0.13						0		0						
FG-1	E	082	0.34	157	0.10					106	0.25	091	0.20						
FG-2	G	095	0.36	170	0.11					340	0.07	325	0.05						

TABLE 1b (continued)

Station	Meter	M_2		S_2		K_2		N_2		K_1		O_1		P_1		M_4		MS_4	
		g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H
FG-2	E	080	0.18	155	0.05					046	0.07	031	0.05						
FG-3	G	085	0.34	160	0.10					071	0.20	061	0.15						
FG-3	E	084	0.32	159	0.09					109	0.12	094	0.09						
G-1	P.W.	148	0.70	198	0.20	191	0.05	050	0.20	315	0.04	300	0.07	312	0.01	311	0.03	180	0.03
G-2	G	194	0.61	244	0.18					220	0.09	205	0.19						
G-2	E	203	0.55	253	0.19					158	0.25	143	0.50						
G-3	G	074	0.45	149	0.14					025	0.35	010	0.28						
G-3	E	194	0.10	269	0.03					309	0.70	294	0.56						
G-4	G	097	0.17	172	0.05					081	0.44	066	0.35						
G-4	E	068	0.20	143	0.06					090	0.30	075	0.24						
G-5	G	046	0.39	121	0.10					298	0.07	283	0.06						
C.E. TR		152	1.09	202	0.22														
C.E. SS		203	0.66	253	0.13														
H-1	P.W.	180	1.19	230	0.24	236	0.07	137	0.22	230	0.06	215	0.12	232	0.02	355	0.07	073	0.07
H-2	G (3 ft)	187	1.15	237	0.24					279	0.06	264	0.12						
H-2	G (11")	185	1.06	235	0.21					351	0.06	336	0.11						
H-2	G (19")	181	1.02	231	0.21					002	0.08	347	0.14						
H-3	G (3")	180	1.03	230	0.21					068	0.09	053	0.18						
H-3	G (11")	173	1.17	223	0.34					235	0.25	220	0.50						
H-3	G (19")	185	0.97	235	0.19					179	0.19	164	0.38						
H-4	G (3")	191	1.34	241	0.28					128	0.05	113	0.10						
H-4	G (7")	190	1.26	240	0.25					148	0.03	133	0.06						
H-4	G (11")	188	1.19	238	0.24					196	0.04	201	0.08						
H-5	G (3")	188	1.52	238	0.31														
H-5	G (5.5")	181	1.39	231	0.29					313	0.21	298	0.43						
H-5	G (8")	184	1.25	234	0.25					313	0.07	298	0.15						
H-6	P.W.	187	1.39	237	0.28					305	0.04	297	0.09						
H-7	G (3")	186	1.34	237	0.27					028	0.08	013	0.15						
H-7	G (9")	188	1.30	238	0.26					280	0.06	265	0.13						
H-7	G (15")	186	0.93	236	0.18					241	0.19	226	0.37						
H-8	G (3")	185	1.14	235	0.25					071	0.05	056	0.09						
H-8	G (6.5")	180	1.00	230	0.20					149	0.03	134	0.06						
H-8	G (10")	175	0.88	225	0.18					088	0.01	073	0.02						
C.E. No. 1		181	1.31	231	0.26														
C.E. No. 1A		190	1.165	240	0.23														
C.E. No. 2		185	1.42	235	0.28														
C.E. No. 2A		185	1.095	235	0.22														
C.E. No. 3		147	0.942	197	0.19														
C.E. No. 3A		166	1.04	216	0.21														
C.E. No. 4		180	1.360	230	0.27														
C.E. No. 5		188	1.285	238	0.26														
C.E. No. 6		193	1.10	243	0.22														
C.E. No. 7		187	0.025	237	0.21														
C.E. No. 8		176	0.985	226	0.20														
C.E. No. 9		154	0.905	204	0.18														
c		184	1.13	234	0.23	242	0.06	124	0.10	230	0.08	215	0.15	244	0.05	326	0.12	052	0.06
C.E. BED		053	0.75	103	0.15														
I-1	G	179	0.74	229	0.14					129	0.06	114	0.12						
I-1	E	215	0.41	265	0.09								0						
I-2	P.W.	192	0.95	242	0.19	236	0.06	169	0.27	195	0.08	180	0.16	184	0.03	340	0.05	112	0.02
I-3	G	194	0.90	244	0.18					176	0.08	161	0.16						
I-3	E	178	0.65	228	0.13					233	0.26	218	0.55						
J-1	G	200	1.59	250	0.32					208	0.17	163	0.25						
J-1	E	192	1.32	242	0.26					210	0.10	165	0.14						
J-2	P.W.	203	1.31	253	0.26	209	0.08	177	0.27	205	0.13	160	0.20	213	0,04		0	094	0.02
J-3	G	216	1.12	266	0.22					250	0.09	205	0.13						
J-3	E	222	0.80	272	0.16					247	0.13	202	0.19						
K-1	G	179	0.68	229	0.12					155	0.18	110	0.18						
K-2	G	218	1.03	268	0.17					226	0.59	181	0.59						
K-2	E	215	0.70	265	0.11					347	0.67	302	0.67						
K-3	G	200	0.90	250	0.15					315	0.08	270	0.08						
K-3	E	165	0.58	215	0.09					207	0.33	162	0.33						
K-4	G	200	0.77	250	0.13					263	0.16	217	0.16						
K-4	E	213	0.26	263	0.06					020	0.23	335	0.23						

TABLE 1b (continued)

		M_2		S_2		K_2		N_2		K_1		O_1		P_1		M_4		MS_4	
Station	Meter	g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H	g	H
K-5	P.W.	203	1.20	~~253~~	~~0.20~~	257	0.04	115	0.20	~~190~~	~~0.28~~	~~145~~	~~0.28~~	177	0.10	139	0.06	008	0.20
K-6	G	209	1.45	259	0.24					188	0.25	143	0.25						
K-6	E	212	1.01	262	0.17					170	0.20	125	0.20						
K-7	G	218.	1.23	268	0.21					207	0.27	162	0.27						
K-7	E	212	1.02	262	0.17					189	0.19	144	0.19						
K-8	G	207	1.22	257	0.20					203	0.22	158	0.22						
K-8	E	206	1.05	256	0.17					267	0.15	222	0.15						
K-9	G	213	0.91	263	0.15					194	0.21	149	0.21						
K-9	E	205	0.99	255	0.17					230	0.35	185	0.35						
K-10	P.W.	195	1.25	245	0.21					174	0.29	129	0.29						
d		203	1.09	~~253~~	0.18	248	0.06	214	0.24	~~190~~	0.22	145	0.22	200	0.08	226	0.08	332	0.08
L-1	P.W.*	085	0.16	139	0.02					227	0.48	184	0.44						
L-2	G	146	0.09	196	0.03					198	0.30	153	0.30						
L-2	E	160	0.22	210	0.04					128	0.09	083	0.09						
L-3	G	161	0.30	211	0.04					315	0.11	270	0.11						
L-3	E	097	0.16	147	0.03					148	0.14	103	0.14						
L-4	G	185	0.55	235	0.10					243	0.13	197	0.13						
L-4	E	129	0.40	179	0.06					254	0.19	209	0.19						

P.W. : Paddle Wheel Current Meter Stations of periods ranging from 7 to 25 days.
P.W.*: Paddle Wheel Current Meter Station of less than 7 days.
G : 25-hour Gurley Meter Current Stations.
E : 25-hour Ekman Meter Current Stations.
C.E. : Consultant Engineers' 13-hour current stations.

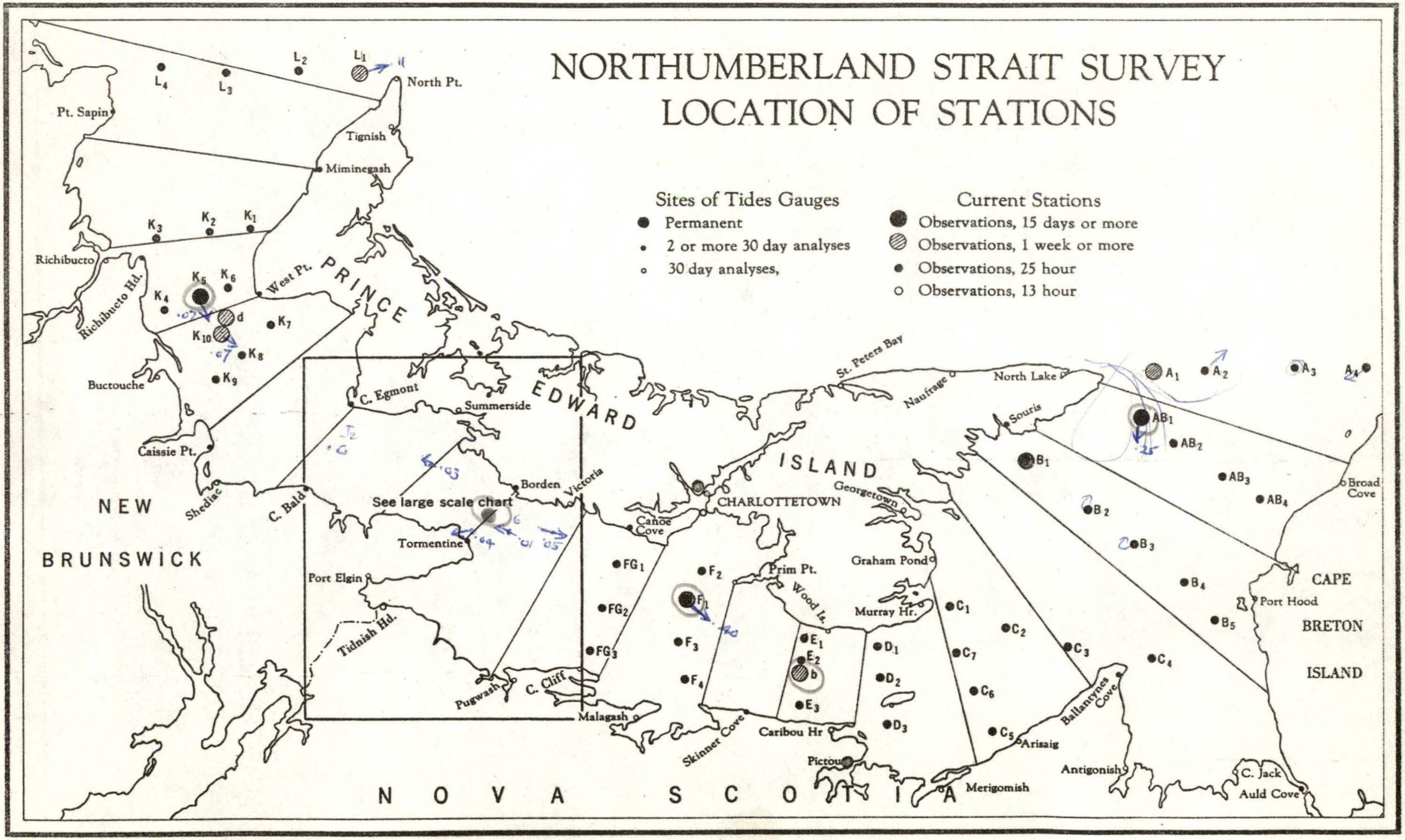

NORTHUMBERLAND STRAIT SURVEY
LOCATION OF STATIONS
Sites of Tides Gauges
Permanent
2 or more 30 day analyses
30 day analyses,
Current Stations
Observations, 15 days or more
Observations, 1 week or more
Observations, 25 hour
Observations, 13 hour
North Pt.
Pt. Sapin
Tignish
Miminegash
Richibucto
Richibucto Hd.
West Pt.
PRINCE
EDWARD
ISLAND
Buctouche
Caissie Pt.
Shediac
C. Bald
C. Egmont
Summerside
Borden
Victoria
See large scale chart
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
NEW
BRUNSWICK
NOVA SCOTIA
CHARLOTTETOWN
Canoe Cove
St. Peters Bay
Naufrage
North Lake
Souris
Georgetown
Graham Pond
Prim Pt.
Wood Is.
Murray Hr.
Skinner Cove
Caribou Hr
Pictou
Merigomish
Arisaig
Ballantynes Cove
Antigonish
C. Jack
Auld Cove
Broad Cove
Port Hood
CAPE BRETON ISLAND

Fig. 1a.

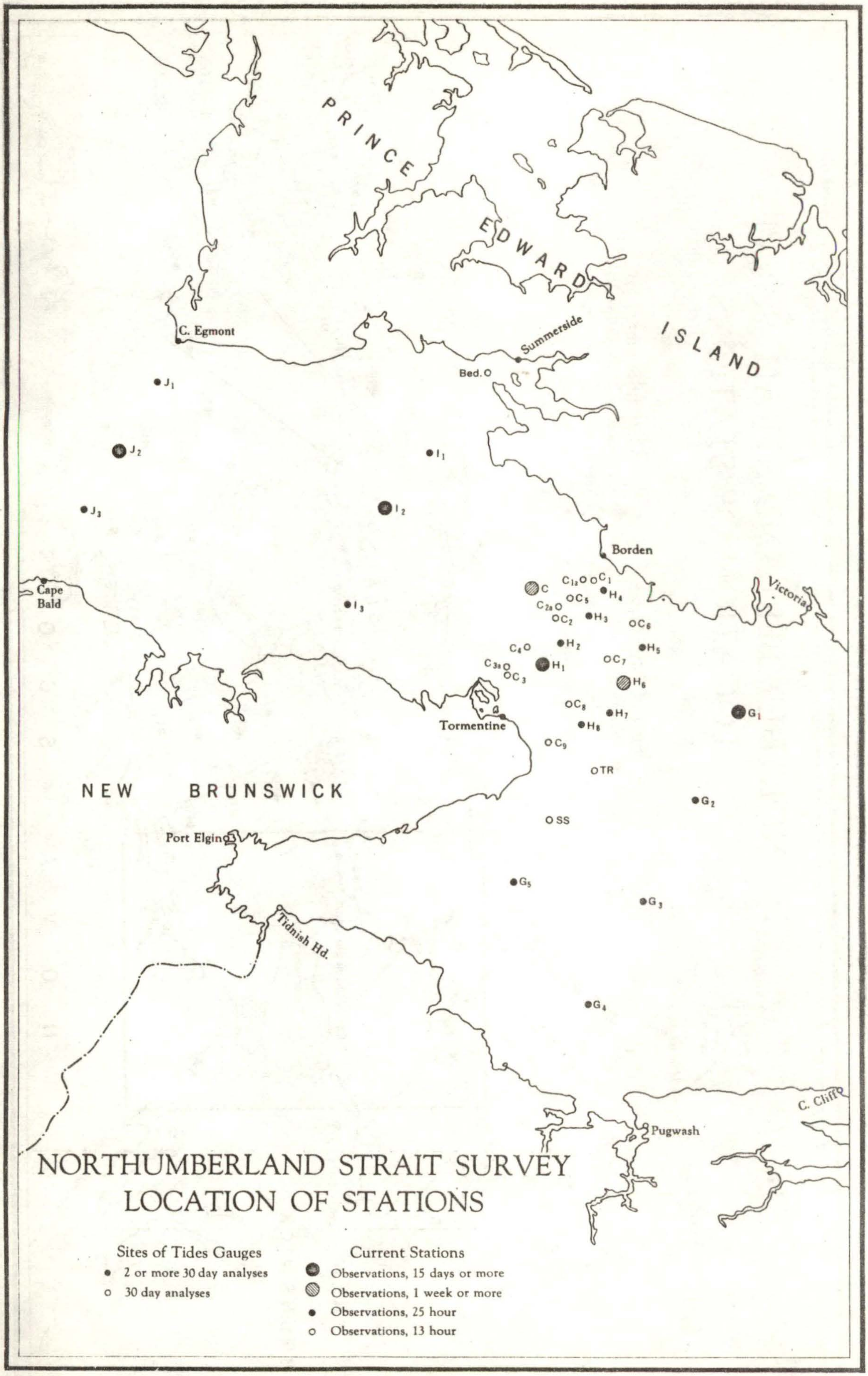

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Bed. O
J1
J2
J3
I1
I2
I3
Borden
Cape Bald
Victoria
C
C1
C1a
C2a
C2
C5
C6
H4
H3
H2
H5
C4
C3a
C3
H1
C7
H6
C8
H7
H8
G1
Tormentine
C9
TR
NEW BRUNSWICK
G2
SS
Port Elgin
G5
G3
Tidnish Hd.
G4
C. Cliff
Pugwash
NORTHUMBERLAND STRAIT SURVEY
LOCATION OF STATIONS
Sites of Tides Gauges
2 or more 30 day analyses
30 day analyses
Current Stations
Observations, 15 days or more
Observations, 1 week or more
Observations, 25 hour
Observations, 13 hour

Fig. 1b.

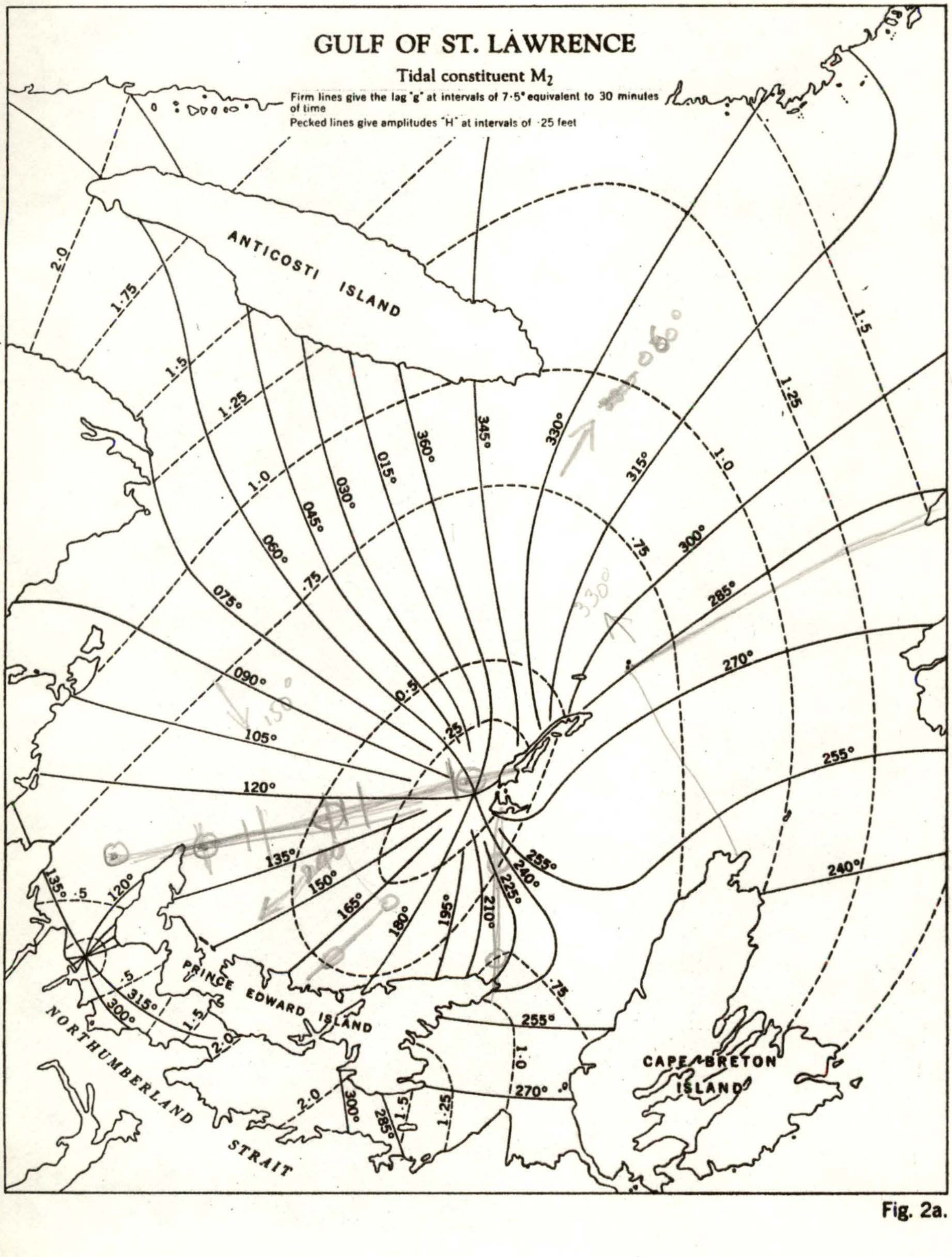

GULF OF ST. LAWRENCE
Tidal constituent M2
Firm lines give the lag "g" at intervals of 7·5° equivalent to 30 minutes of time
Pecked lines give amplitudes "H" at intervals of ·25 feet
ANTICOSTI ISLAND
PRINCE EDWARD ISLAND
CAPE BRETON ISLAND
NORTHUMBERLAND STRAIT
2·0
1·75
1·5
1·25
1·0
·75
0·5
·25
345°
360°
330°
315°
300°
285°
270°
255°
240°
015°
030°
045°
060°
075°
090°
105°
120°
135°
150°
165°
180°
195°
210°
225°

Fig. 2a.

2. THE EXISTING TIDAL CONDITIONS

The Semidiurnal Tide in the Gulf of St. Lawrence

The tides in the Gulf are generated by the oceanic tides reaching Cabot Strait and the Strait of Belle Isle, but principally by the former.

The propagation of the semidiurnal constituent M_2 is depicted in Figure 2a, page 16; there the firm lines are cotidal lines, each of which joins points at which high water occurs simultaneously, while the pecked lines are co-range lines, each of which joins points at which the amplitude, and therefore the range, are similar. The high-water angles against the cotidal lines are "g", the phase-lag of M_2; the figures against the pecked lines are "H", the amplitude of M_2. An amphidromic point, at which the amplitude of M_2 is zero, lies off the south-western part of Magdalen Islands. The cotidal lines radiate from this point and the high water angles against these lines become greater in an anticlockwise progression round the Gulf. The change between any adjacent pair of cotidal lines is 15°, equivalent to a change of 31 minutes in the time of high water, and the progression round the gulf is completed in the semidiurnal period of 12 hours 25 minutes. Because of this progression, the semidiurnal tide reaches the western entrance of Northumberland Strait several hours before it reaches the eastern entrance. At the latter, the semidiurnal oscillation is a combination of that which has circulated round the Gulf and the next incoming oscillation through Cabot Strait.

The Semidiurnal Tide in Northumberland Strait

The propagation of the semidiurnal constituent M_2 in the Strait is shown in greater detail in Figures 2b and 2c, pages 18 and 19 from the final report of

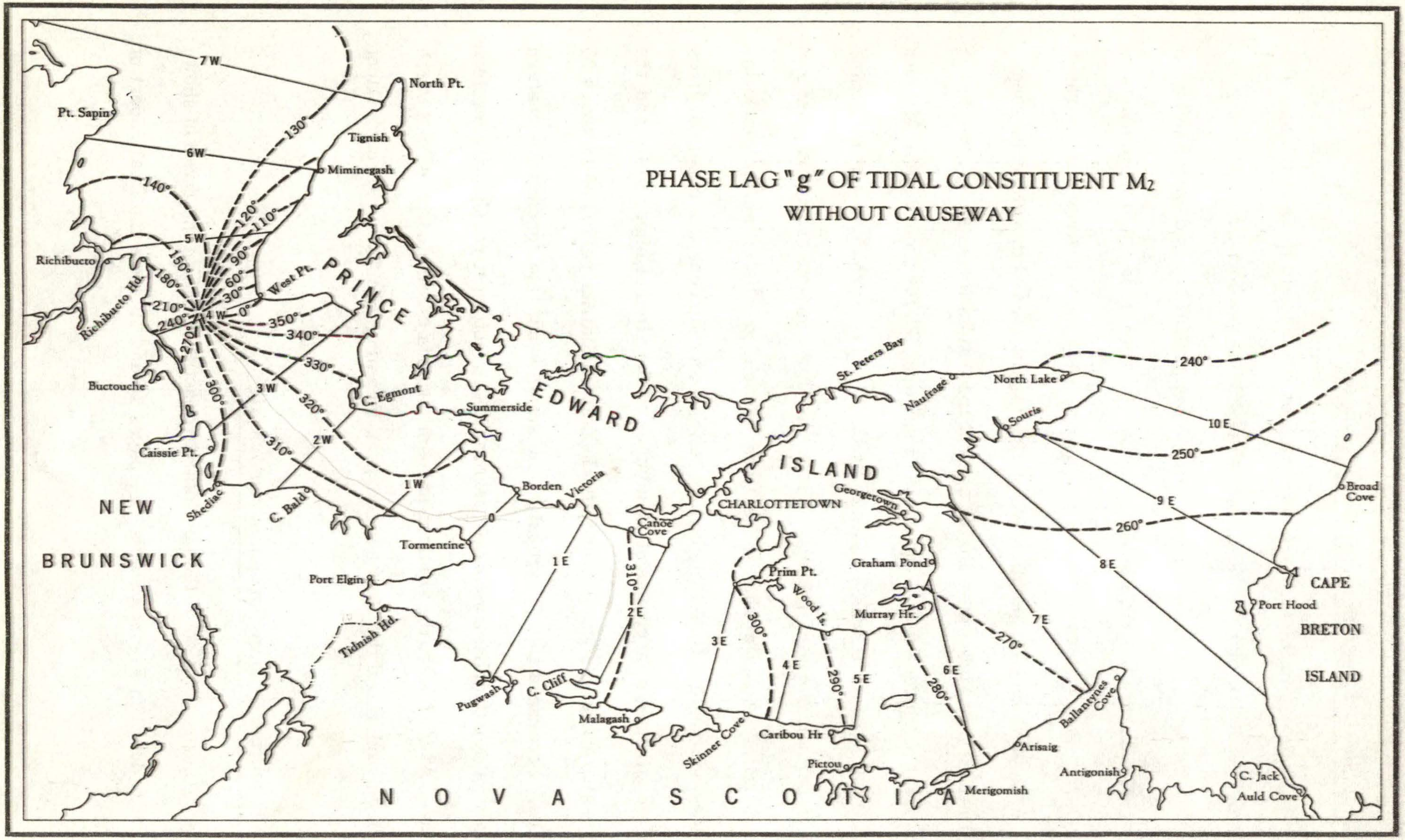

PHASE LAG "g" OF TIDAL CONSTITUENT M2
WITHOUT CAUSEWAY
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
CAPE BRETON ISLAND
CHARLOTTETOWN
North Pt.
Pt. Sapin
Tignish
Miminegash
Richibucto
Richibucto Hd.
West Pt.
Buctouche
C. Egmont
Summerside
Caissie Pt.
Shediac
C. Bald
Borden
Victoria
Tormentine
Canoe Cove
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Skinner Cove
Caribou Hr
Pictou
Prim Pt.
Wood Is.
Murray Hr.
Graham Pond
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
Broad Cove
Port Hood
Ballantynes Cove
Arisaig
Antigonish
Merigomish
C. Jack
Auld Cove
7 W
6 W
5 W
4 W
3 W
2 W
1 W
0
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E
0°
30°
60°
90°
110°
120°
130°
140°
150°
180°
210°
240°
270°
300°
310°
320°
330°
340°
350°
240°
250°
260°
270°
280°
290°
300°
310°

Fig. 2b.

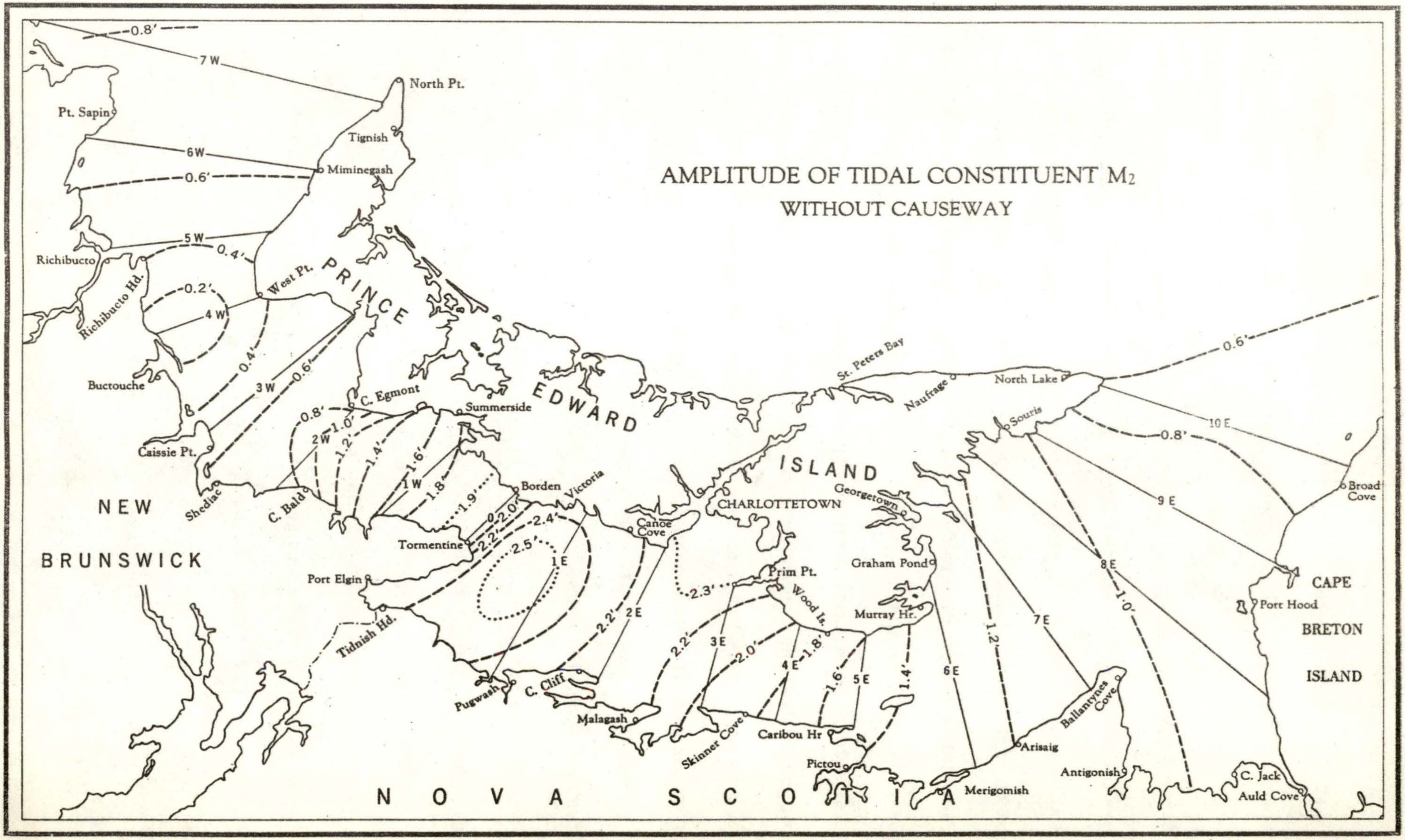

AMPLITUDE OF TIDAL CONSTITUENT M2
WITHOUT CAUSEWAY
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
CAPE BRETON ISLAND
CHARLOTTETOWN
North Pt.
Tignish
Miminegash
West Pt.
Pt. Sapin
Richibucto
Richibucto Hd.
Buctouche
Caissie Pt.
Shediac
C. Bald
C. Egmont
Summerside
Borden
Victoria
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Canoe Cove
Prim Pt.
Wood Is.
Skinner Cove
Caribou Hr
Pictou
Merigomish
Arisaig
Ballantynes Cove
Antigonish
C. Jack
Auld Cove
Port Hood
Broad Cove
Graham Pond
Murray Hr.
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
7 W
6 W
5 W
4 W
3 W
2 W
1 W
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E
0.8'
0.6'
0.4'
0.2'
1.0'
1.2'
1.4'
1.6'
1.8'
1.9'
2.0'
2.2'
2.4'
2.5'
2.3'

Fig. 2c.

the Tidal Institute*. When the oscillation from the eastern entrance reaches Section 2 E the angle is 310°, which differs by 180° from the angle in the western entrance, indicating that high water at one of these places coincides with low water at the other.

The narrows off Cape Tormentine form a partial barrier between the eastern and western halves of the Strait, the effect of which is that some of the oscillation from the east is reflected back, resulting in an increase in range in that part of the Strait. The rest of the oscillation is propagated through the narrows in direct opposition to the oscillation from the western entrance. The combination of two oscillations, differing in phase by 180° and travelling in opposite directions, creates a standing oscillation in the western part. The amphidromic point, where the two oscillations counter-balance each other, lies between Buctouche, New Brunswick, and West Point, Prince Edward Island. It is high water on one side of this amphidromic point when it is low water on the other side. Throughout the western part of the Strait the amplitude of M_2 increases with distance from this point.

The Diurnal Tide in the Gulf of St. Lawrence

The propagation of the diurnal constituent K_1, in the Gulf is depicted on Figure 2d, page 21. The firm lines are cotidal lines, along each of which high water occurs simultaneously. The high-water angles against these lines are the phase lags "g" of K_1, and the change between any pair of adjacent lines is 7.5 degrees, equivalent to a change of about 30 minutes in the times of high water. The pecked lines show the changes in the amplitudes of K_1.

With this constituent, the amphidromic point lies far outside the Gulf, and the cotidal line, 217.5 degrees, extends right across the Gulf from Cabot

* Appendix B2

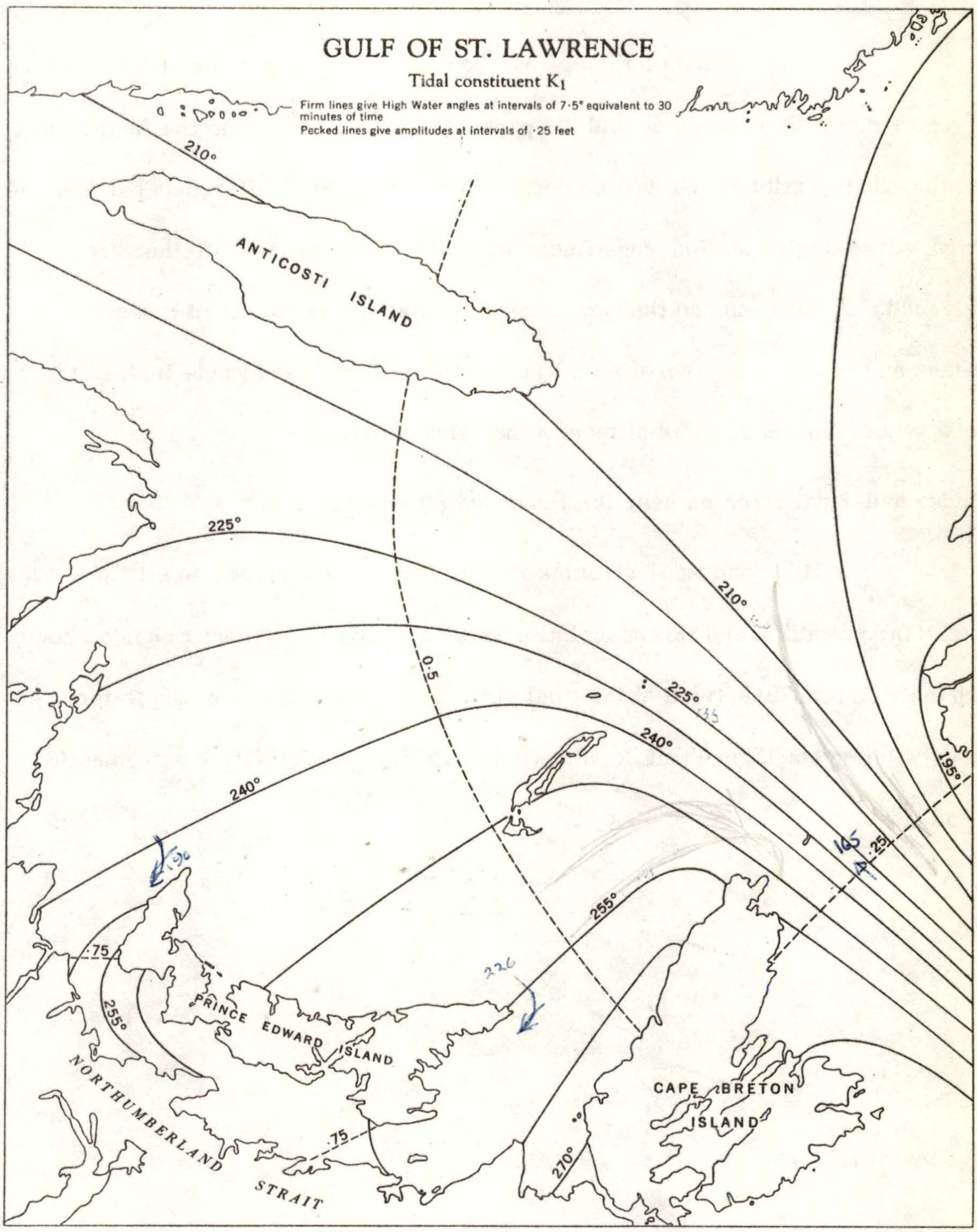

GULF OF ST. LAWRENCE
Tidal constituent K1
Firm lines give High Water angles at intervals of 7·5° equivalent to 30 minutes of time
Pecked lines give amplitudes at intervals of ·25 feet
210°
ANTICOSTI ISLAND
225°
210°
0.5
225°
240°
240°
195°
·25
255°
·75
255°
PRINCE EDWARD ISLAND
NORTHUMBERLAND STRAIT
·75
CAPE BRETON ISLAND
270°

Fig. 2d.

Strait to the St. Lawrence estuary. Northeastwards of this line high water occurs progressively earlier, and to the southwestward it occurs progressively later.

The Diurnal Tide in Northumberland Strait

The propagation of the diurnal constituent K_1 in the Strait is shown in greater detail on Figures 2e and 2f, pages 23 and 24, also from the final report of the Tidal Institute*. It will be seen that there is little difference between the high-water angles of this constituent when the two entrances to the Strait are reached. In consequence the two diurnal oscillations in the Strait are nearly in phase and in this case there is no conflict between east and west, instead there is a general increase in amplitude in the central part.

Tides and Tidal Streams near the Proposed Site of the Causeway

The tides and tidal streams in this area are described in still greater detail in Appendix A and this description is accompanied by synoptic charts showing the rates and directions of the tidal streams, and the levels of the water, at hourly intervals throughout November 13, 1958, a day of fairly extreme tidal conditions.

* Appendix B2

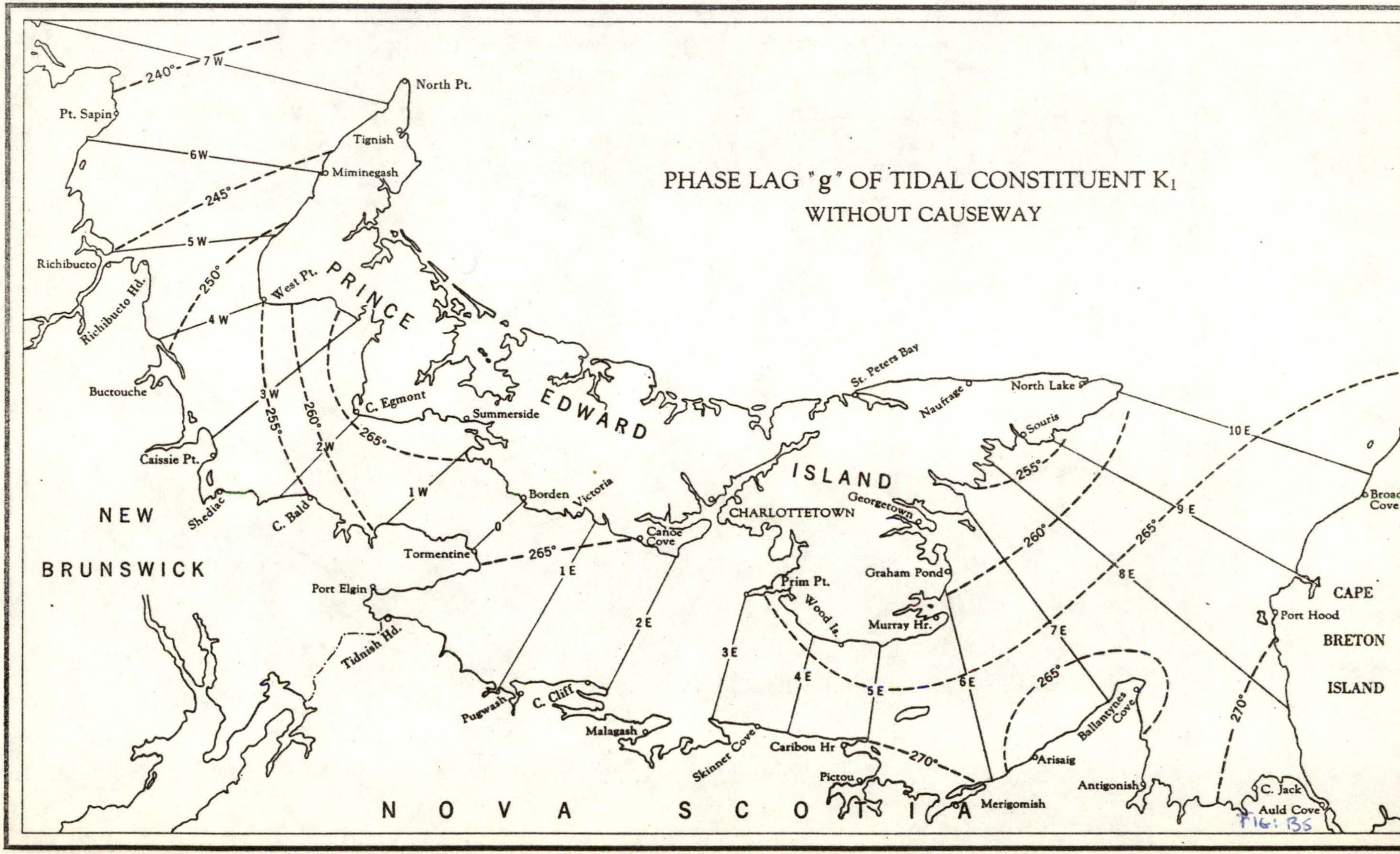

PHASE LAG "g" OF TIDAL CONSTITUENT K1
WITHOUT CAUSEWAY
North Pt.
Pt. Sapin
Tignish
Miminegash
Richibucto
Richibucto Hd.
West Pt.
PRINCE
EDWARD
ISLAND
Buctouche
Caissie Pt.
C. Egmont
Summerside
Shediac
C. Bald
Borden
Victoria
Canoe Cove
CHARLOTTETOWN
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
Broad Cove
NEW
BRUNSWICK
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Skinner Cove
Caribou Hr
Pictou
Merigomish
Prim Pt.
Wood Is.
Murray Hr.
Graham Pond
Arisaig
Ballantynes Cove
Antigonish
C. Jack
Auld Cove
Port Hood
CAPE
BRETON
ISLAND
NOVA SCOTIA
240°
245°
250°
255°
260°
265°
270°
7W
6W
5W
4W
3W
2W
1W
0
1E
2E
3E
4E
5E
6E
7E
8E
9E
10E

Fig. 2e.

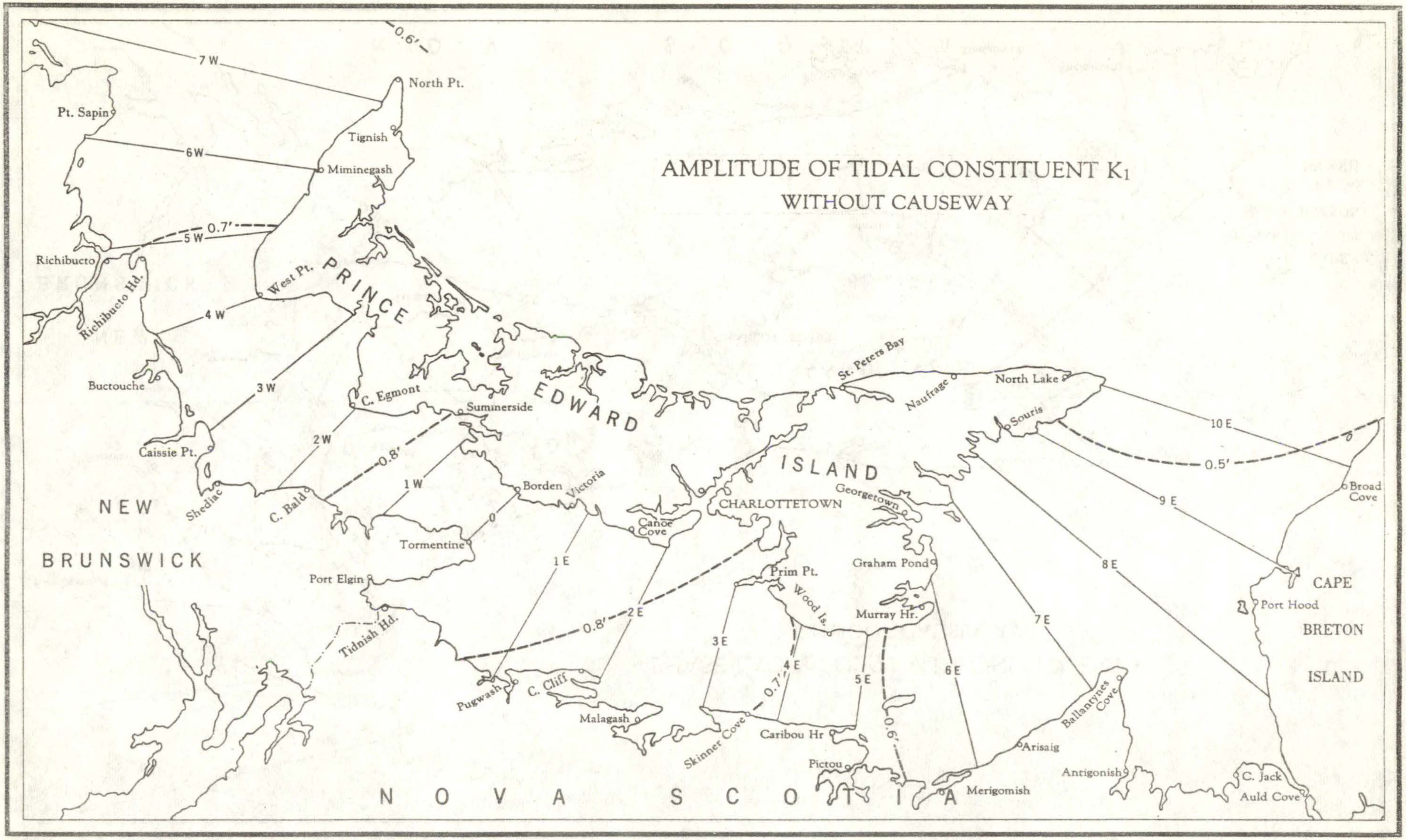

AMPLITUDE OF TIDAL CONSTITUENT K1
WITHOUT CAUSEWAY
0.6′
7 W
North Pt.
Pt. Sapin
Tignish
6W
Miminegash
0.7′
5 W
Richibucto
West Pt.
PRINCE
Richibucto Hd.
4 W
Buctouche
3 W
C. Egmont
Summerside
EDWARD
2 W
Caissie Pt.
0.8′
1 W
Borden
Victoria
ISLAND
NEW
BRUNSWICK
Shediac
C. Bald
0
Tormentine
Canoe Cove
CHARLOTTETOWN
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
10 E
0.5′
9 E
Broad Cove
8 E
Graham Pond
Prim Pt.
Wood Is.
Murray Hr.
Port Elgin
1 E
2 E
0.8′
Tidnish Hd.
3 E
4 E
0.7′
5 E
6 E
7 E
CAPE
Port Hood
BRETON
ISLAND
Pugwash
C. Cliff
Malagash
Skinner Cove
Caribou Hr
0.6′
Pictou
Ballantynes Cove
Arisaig
Antigonish
Merigomish
C. Jack
Auld Cove
N O V A S C O T I A

Fig. 2f.

3. TIDAL CONDITIONS AFTER CONSTRUCTION OF CAUSEWAY

Changes in the Propagation of the Tidal Constituents M_2 and K_1

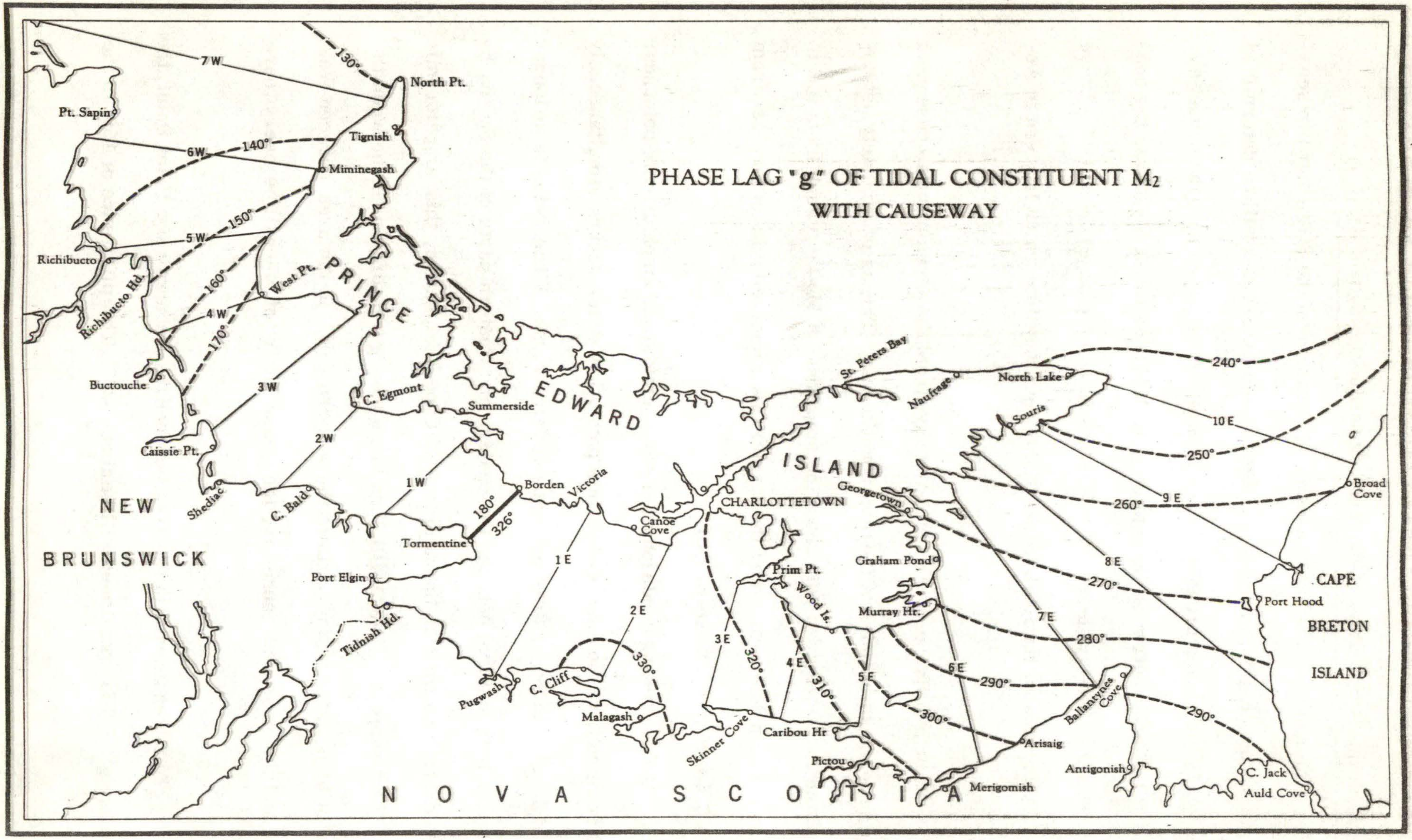
The construction of a causeway will transform the Strait into two separate gulfs. In each, the propagation of the semidiurnal tides will be determined by the length, depth and breadth of the gulf from its entrance up to the causeway.

The propagation of the semidiurnal tidal constituent M_2, after the construction of a causeway, is shown on Figures 3a and 3b, pages 26 and 27. These figures accompanied the final report of the Tidal Institute which is given in Appendix B2.

In both gulfs there is a reflected wave from the barrier and a consequent increase in the amplitudes of the tidal constituents. This is particularly noticeable in the longer eastern gulf where the amplitude of M_2 increases from 0. 6 to 3. 6 feet between the entrance and the barrier, as compared with an increase from 0. 8 to 2. 5 feet in the western gulf.

Under existing conditions there is a semidiurnal amphidromic point near West Point and, to the eastward of this point, low water occurs simultaneously with high water in the western entrance and vice versa. When water is no longer transported, to and fro, between the eastern and western parts of the Strait, by the tidal streams through the narrows off Cape Tormentine, this amphidromic point will disappear. There will then be no very great differences between the times of high water in any parts of the western gulf. In the area between West Point and the proposed causeway, the phase lag "g" of M_2 will be everywhere about 175°.

To the eastward, in the area between the causeway and Prim Point, the phase lag "g" of this constituent will be about 325°. This difference of 150° in the



PHASE LAG "g" OF TIDAL CONSTITUENT M2
WITH CAUSEWAY
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
CAPE BRETON ISLAND
North Pt.
Tignish
Miminegash
Pt. Sapin
Richibucto
Richibucto Hd.
West Pt.
Buctouche
C. Egmont
Summerside
Caissie Pt.
Shediac
C. Bald
Borden
Victoria
Tormentine
Canoe Cove
CHARLOTTETOWN
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
Broad Cove
Graham Pond
Prim Pt.
Wood Is.
Murray Hr.
Port Hood
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Skinner Cove
Caribou Hr
Pictou
Merigomish
Arisaig
Ballantynes Cove
Antigonish
C. Jack
Auld Cove
130°
140°
150°
160°
170°
180°
326°
330°
320°
310°
300°
290°
280°
270°
260°
250°
240°
7 W
6W
5 W
4 W
3 W
2 W
1 W
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E

Fig. 3a.

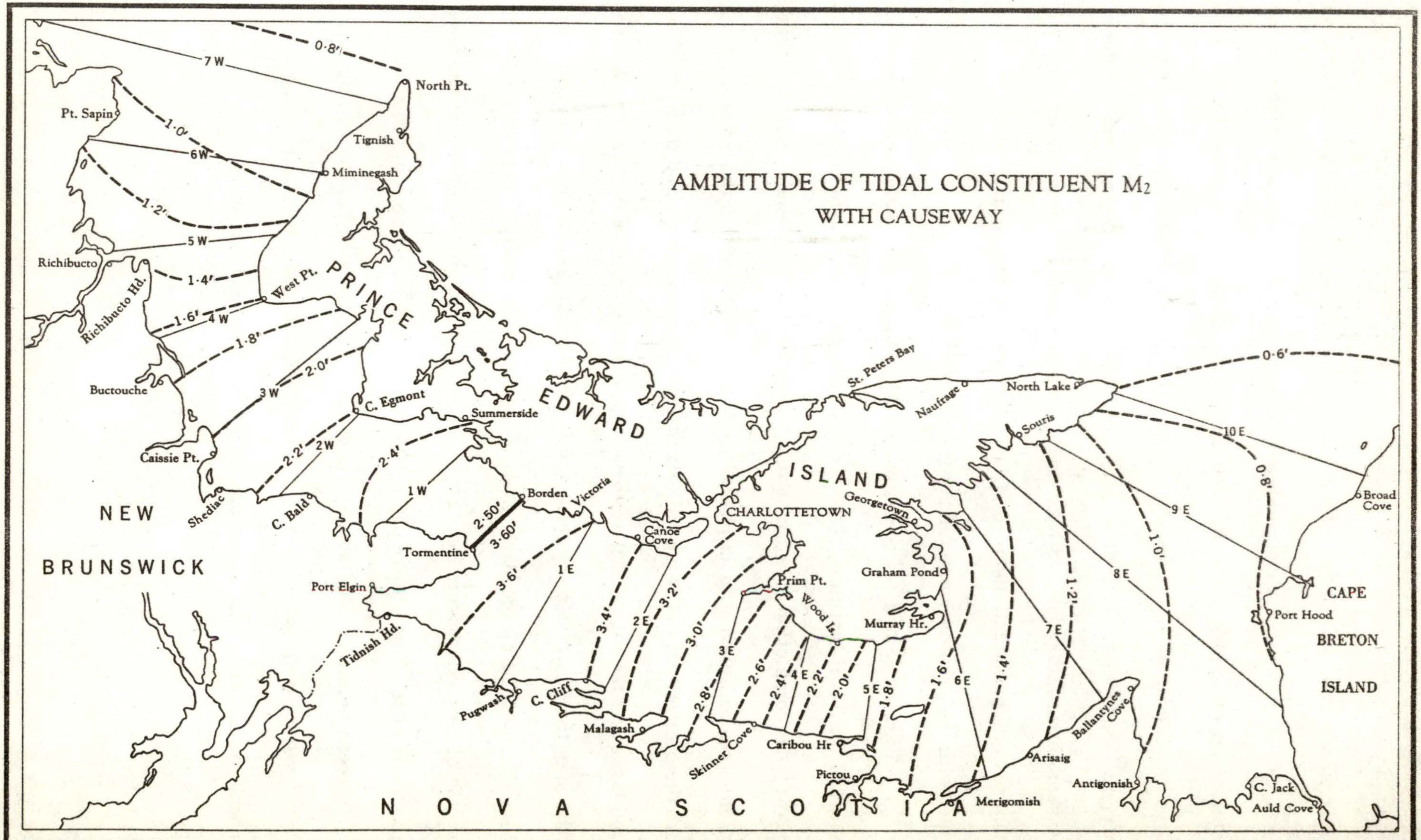

AMPLITUDE OF TIDAL CONSTITUENT M2
WITH CAUSEWAY
NEW
BRUNSWICK
PRINCE
EDWARD
ISLAND
NOVA SCOTIA
CAPE
BRETON
ISLAND
North Pt.
Tignish
Miminegash
Pt. Sapin
Richibucto
Richibucto Hd.
West Pt.
Buctouche
Caissie Pt.
Shediac
C. Bald
C. Egmont
Summerside
Borden
Victoria
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Canoe Cove
CHARLOTTETOWN
Prim Pt.
Wood Is.
Skinner Cove
Caribou Hr
Pictou
Merigomish
Murray Hr.
Graham Pond
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
Broad Cove
Port Hood
Ballantynes Cove
Arisaig
Antigonish
C. Jack
Auld Cove
0·8′
7 W
1·0′
6 W
1·2′
5 W
1·4′
1·6′
4 W
1·8′
2·0′
3 W
2·2′
2 W
2·4′
1 W
2·50′
3·60′
3·6′
1 E
3·4′
2 E
3·2′
3·0′
3 E
2·8′
2·6′
2·4′
4 E
2·2′
2·0′
5 E
1·8′
1·6′
6 E
1·4′
7 E
1·2′
8 E
1·0′
9 E
0·8′
10 E
0·6′

Fig. 3b.

phase lags on either side of the causeway indicates that the occurrences of high water on one side, and of low water on the other, differ in time by only about an hour. In consequence, about midway between the occurrences of high and low water on opposite sides, the difference in level will be nearly equal to the sums of the amplitudes of M_2, 3. 6 and 2. 5 feet to the eastward and westward respectively, or about 6 feet. This difference in level will be the average amount due to the semidiurnal tide, but, as that tide varies in range by about 50 per cent with changes in the phase and distance of the moon, the difference in level will be about 9 feet with the greatest semidiurnal tides.

Figures 3c and 3d, pages 29 and 30, which also accompanied the final report of the Tidal Institute, show the propagation of the diurnal tidal constituent K_1 after the completion of a causeway. There is not at present, nor will there be, any great difference in the phase lags of this constituent in the two entrances . With the open Strait, the two oscillations are not in opposition and their combination increases the range of the diurnal tide in the central part of the Strait. The division of the Strait into separate gulfs will have no great effect upon this tide. There will still be an increase in the range near the central part of the Strait because of reflection from the barrier, and no great difference in the range on either side of it. The difference in the phase lags, which amounts to about 35° in the areas on either side of the causeway, will have a rather more important effect. With the greatest diurnal tide this phase difference would cause a difference, on the two sides of the causeway, of about one foot (in the levels of this tide).

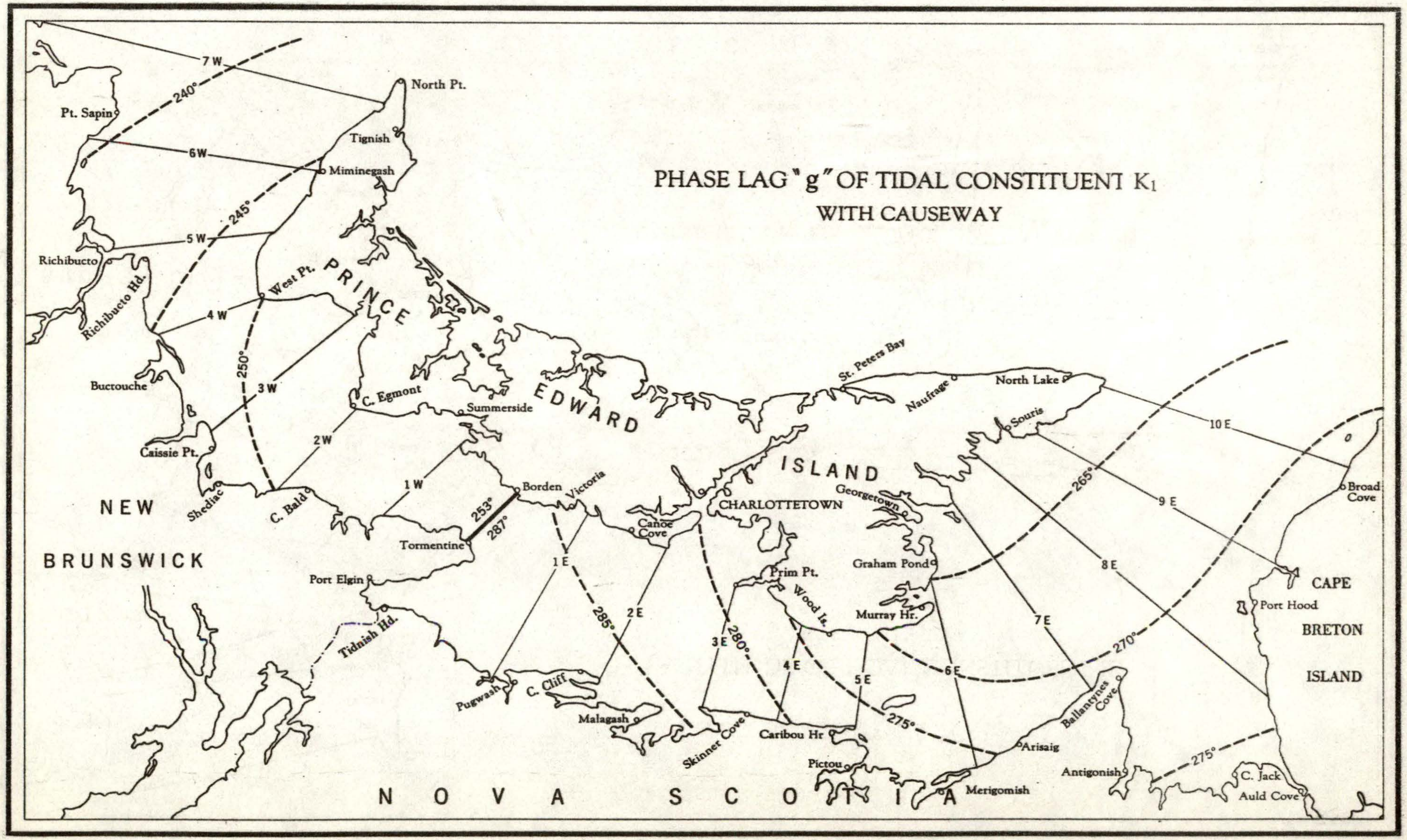
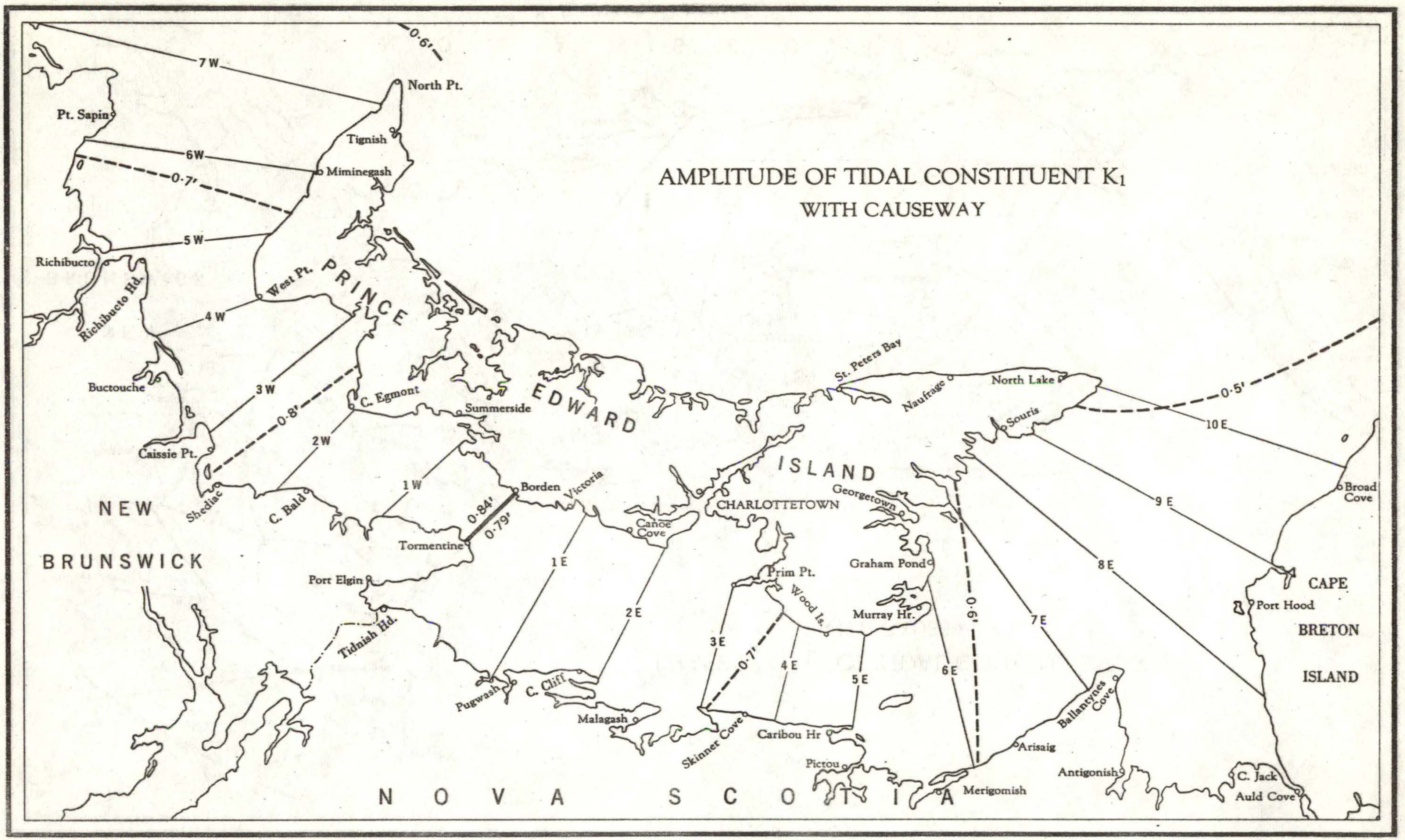

PHASE LAG "g" OF TIDAL CONSTITUENT K1
WITH CAUSEWAY
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
CAPE BRETON ISLAND
CHARLOTTETOWN
North Pt.
Tignish
Miminegash
Pt. Sapin
Richibucto
Richibucto Hd.
West Pt.
Buctouche
C. Egmont
Summerside
Caissie Pt.
Shediac
C. Bald
Borden
Victoria
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Canoe Cove
Skinner Cove
Caribou Hr
Pictou
Merigomish
Prim Pt.
Wood Is.
Murray Hr.
Graham Pond
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
Broad Cove
Port Hood
Ballantynes Cove
Arisaig
Antigonish
C. Jack
Auld Cove
7 W
6 W
5 W
4 W
3 W
2 W
1 W
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E
240°
245°
250°
253°
287°
265°
270°
275°
280°
285°

Fig. 3c.



AMPLITUDE OF TIDAL CONSTITUENT K1
WITH CAUSEWAY
North Pt.
Pt. Sapin
Tignish
Miminegash
Richibucto
Richibucto Hd.
West Pt.
PRINCE
EDWARD
ISLAND
Buctouche
C. Egmont
Summerside
Caissie Pt.
Shediac
C. Bald
Borden
Victoria
Tormentine
NEW
BRUNSWICK
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Canoe Cove
CHARLOTTETOWN
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
Prim Pt.
Wood Is.
Graham Pond
Murray Hr.
Skinner Cove
Caribou Hr
Pictou
Merigomish
Arisaig
Ballantynes Cove
Antigonish
C. Jack
Auld Cove
Port Hood
Broad Cove
CAPE
BRETON
ISLAND
NOVA SCOTIA
7 W
6W
5 W
4 W
3 W
2 W
1 W
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E
0·6'
0·7'
0·8'
0·84'
0·79'
0·5'

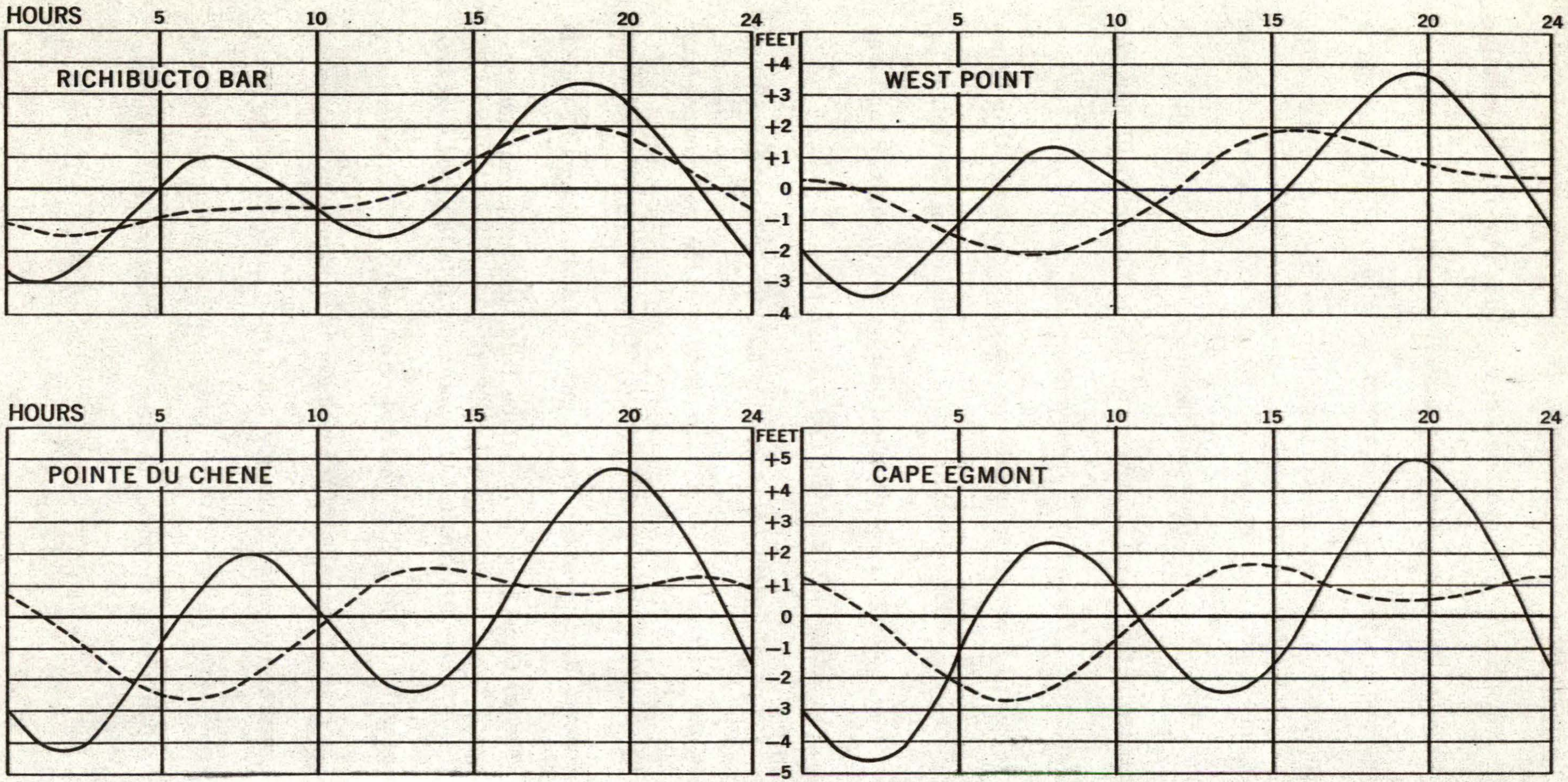
Fig. 3d.

Changes in the Resultant Tide

The characteristics of the resultant tide are determined by the relative magnitudes and phases of the semidiurnal and diurnal components.

In the area immediately to the eastward of the causeway, the changes in the phase lags of the two components are very similar; each will have high water rather less than an hour later than under existing conditions. There will be an increase of 30 to 50 per cent in the amplitude of the semidiurnal component, with no significant increase in the diurnal component. These changes will have no marked effects upon the characteristics of the resultant tide; it will simply arrive later, the high waters will rise higher and the low waters fall lower, than formerly. The resultant tides, under the astronomical conditions of November 13, 1958, with and without a causeway, are depicted on Figure 3f, page 33 for three places in the area, Charlottetown, Victoria and Tidnish Head.

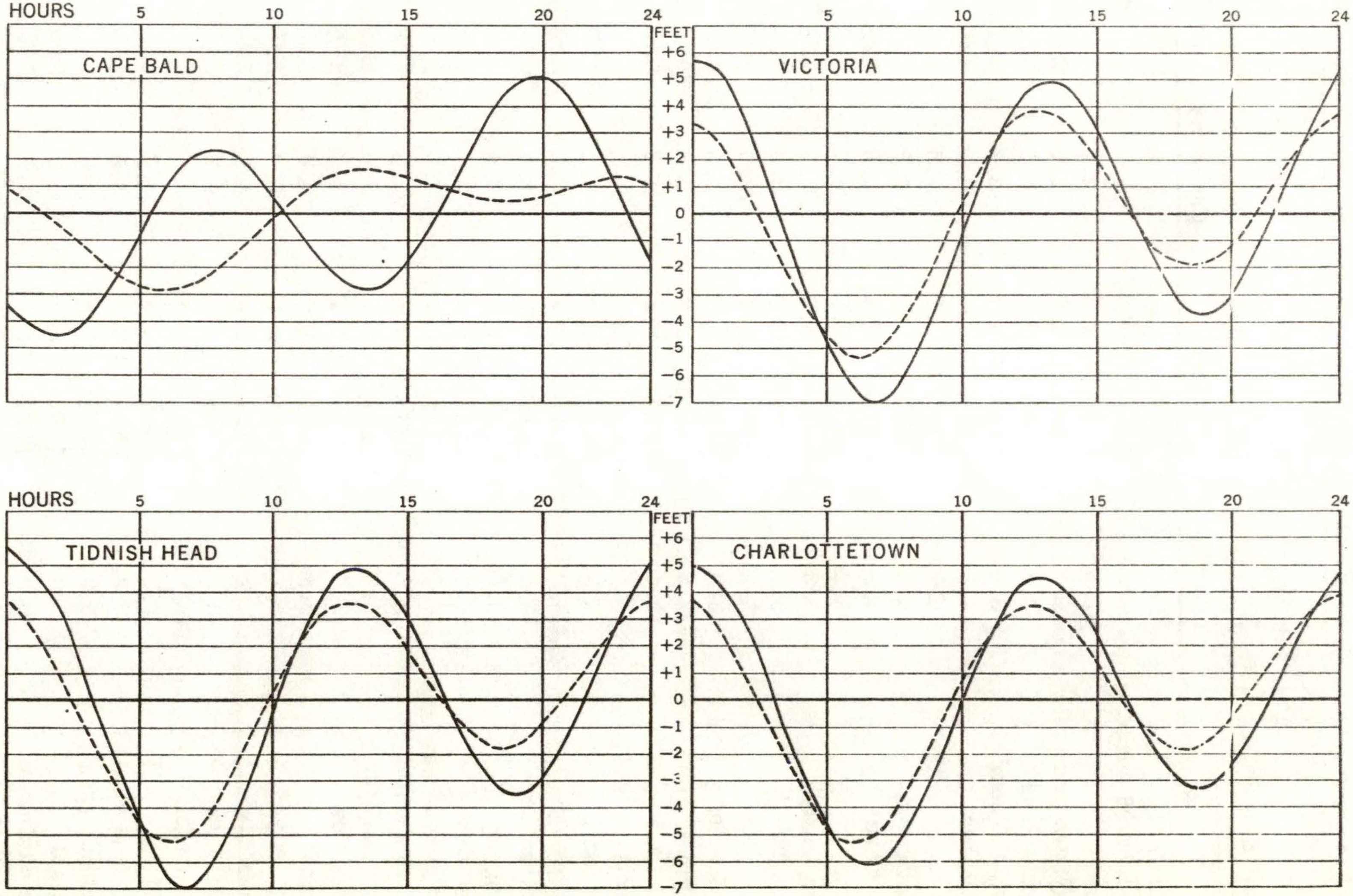
To the westward of the causeway, as far as Buctouche, there will be large alterations in the relative phases and amplitudes of the two components, owing to great changes in the semidiurnal component with no corresponding changes in the diurnal component. It will be seen from Figures 3e and 3f, pages 32 and 33, that at Pointe du Chene, Cape Egmont and Cape Bald, the resultant tide has, under existing conditions, one very marked low water which falls a good deal farther below mean sea level than either high water rises above it. With a causeway, and the consequent increase in the range of the semidiurnal component, the resultant tide will have a greater range than formerly, but, owing to the change in phase relationship, the level of the higher of the two high waters will be raised by a greater amount than the level of the lower of the two low waters is lowered.



Tidal conditions for Nov. 13 1958

- - - - - Without causeway
——— With causeway

Fig. 3e.



Tidal conditions for Nov. 13 1958

- - - - - Without causeway
——— With causeway

Fig. 3f.

TABLE 3a

CHANGES, IN MEAN RANGES OF TIDE, WITH CAUSEWAY

PLACE	RESULTANT TIDE			SEMIDIURNAL TIDE	
	Range = (H. H. W. - L. L. W.)			Range = 2(H of M_2)	
	Without Causeway	Increase with Causeway		Without Causeway	Increase
	Feet	%	Feet	Feet	%
Prince Edward Island					
Souris	3.5	9%	0.3	2.3	13%
Georgetown	3.7	18%	0.7	2.6	24%
Grahams Pond	3.7	26%	0.9	2.5	36%
Murray Harbour	3.9	18%	0.7	2.7	24%
Wood Islands	4.9	19%	0.9	3.6	23%
Prim Point	6.2	17%	1.1	4.6	26%
Charlottetown	6.4	23%	1.5	4.8	38%
Canoe Cove	5.9	41%	2.4	4.5	52%
Victoria	6.2	40%	2.5	4.7	56%
Borden (east)	5.3	61%	3.3	3.8	88%
Borden (west)	5.3	28%	1.2	3.8	30%
Summerside	5.2	27%	1.4	3.5	36%
Cape Egmont	3.0	105%	3.1	1.5	189%
West Point	2.5	93%	2.3	0.8	300%
Miminegash	2.4	32%	0.8	1.2	43%
Nova Scotia					
Port Hood	2.9	- 10%	-0.3	1.8	- 11%
Auld Cove	3.0	1%	0	1.5	- 2%
Ballantyne Cove	3.2	1%	0	2.0	0
Arisaig	3.6	- 3%	-0.1	2.4	1%
Merigomish	3.9	1%	0	2.7	4%
Pictou Island	4.1	17%	0.7	2.9	24%
Pictou Harbour	3.9	19%	0.7	2.6	41%
Caribou Harbour	4.2	14%	0.6	3.0	20%
Skinners Cove	5.0	27%	1.4	3.7	37%
Malagash	5.8	27%	1.5	4.4	36%
Cape Cliff	5.8	45%	2.6	4.3	57%
Pugwash	6.1	42%	2.5	4.7	50%
Tidnish Head	6.3	37%	2.4	4.8	50%
New Brunswick					
Port Elgin	6.3	38%	2.4	4.7	52%
Tormentine (east)	5.2	67%	3.5	3.8	88%
Tormentine (west)	5.2	29%	1.5	3.8	30%
Cape Bald	3.0	109%	3.3	1.6	184%
Pointe du Chene	2.8	112%	3.1	1.3	223%
Caissie Point	2.5	117%	3.3	1.0	285%
Crossman Point	2.1	150%	3.1	0.4	718%
Richibucto Bar	2.3	68%	1.5	0.9	211%
Point Sapin	2.7	33%	0.9	1.3	72%

Between the existing amphidromic point and the western entrance, the effect of a causeway upon the present phase relationship will be small and the higher high-water level will be raised, and the lower low-water level lowered, by nearly corresponding amounts.

Changes in the Range of the Tide

The Department of Public Works, in dealing with siltation and dredging problems, is concerned with the percentage changes in the range of the tide. The increases in the range of the semidiurnal component are much greater than those of the diurnal component, so that the percentage increases in the former are much greater than those in the resultant of the two components. The mean range of the semidiurnal component is equal to 2 (H of M_2), whereas the mean range of the resultant tide is given as the difference between the mean level of the higher high water and that of the lower low water. Thus, the former is the average of the rise and fall occurring four times a day, whereas the latter is the largest rise or fall which occurs only once a day. In considering the transport of material in suspension, the large rise or fall may outweigh in importance that of the average rise and fall. For this reason the mean ranges of the semidiurnal component and of the resultant tide are given in Table 3a with the actual and percentage increases in those ranges with a causeway. The actual increases in the mean range of the resultant tide are depicted on Figure 3g, page 38; this shows that the greatest increases are to be expected in the area near Cape Egmont and immediately to the eastward of the causeway.

Changes in the High-water and Low-water Tidal Levels

It is the changes in the levels occurring with fairly extreme tidal conditions which are of importance, and these have been computed by formula from the harmonic constants, for all the tide-gauge sites in the Strait, without and with a causeway. It is not possible to define exactly what are extreme tidal conditions, mainly for the reason that the greatest diurnal tides can only occur near the solstices, while the greatest semidiurnal tides can only occur near the equinoxes. For some tide-gauge sites, the higher high-water and the lower low-water levels have been predicted for the fairly extreme tidal conditions of November 13, 1958, and in all cases these levels are in good agreement with those computed by formula.

The higher high-water levels and the lower low-water levels, for existing conditions, and the changes in those levels which will be brought about by the construction of a causeway, have been computed on the basis of the harmonic constants given in Table B1a, Appendix B1, and the results are listed in Table 3b, facing.

It has been explained earlier that as a result of the change in the phase relationship between the semidiurnal and diurnal components in the area between Buctouche and the causeway, the levels of higher high water will be raised to a greater extent than that by which the levels of lower low water will be depressed. The changes in the higher high-water levels are given also on Figure 3h, page 39 and this shows that increased elevations of 2.5 feet or more will be confined to the area extending westwards from the causeway to West Point.

TABLE 3b

CHANGES, UNDER FAIRLY EXTREME ASTRONOMICAL CONDITIONS, WITH CAUSEWAY

PLACE	RESULTANT TIDE UNDER FAIRLY EXTREME ASTRONOMICAL CONDITIONS					
	Without Causeway			Changes with Causeway		
	H. H. W. above M. S. L. feet	L. L. W. below M. S. L. feet	Range feet	H. H. W. Rise feet	L. L. W. Fall feet	Range Increase feet
Prince Edward Island						
Souris	2.4	2.9	5.3	0.3	0.1	0.4
Georgetown	2.6	3.1	5.7	0.2	0.3	0.4
Grahams Pond	2.4	3.2	5.6	0.6	0.5	1.1
Murray Harbour	2.7	3.2	5.9	0.2	0.4	0.6
Wood Islands	3.0	4.0	7.0	0.6	0.5	1.1
Prim Point	3.7	4.4	8.1	0.8	1.1	1.9
Charlottetown	4.1	5.1	9.2	0.7	0.6	1.4
Canoe Cove	3.6	5.0	8.6	1.7	1.3	2.9
Victoria	3.9	5.4	9.3	1.6	1.1	2.7
Borden (east)	3.2	4.6	7.8	2.2	1.6	3.9
Borden (west)	3.2	4.6	7.8	2.2	0.2	2.4
Summerside	3.1	4.2	7.3	2.3	0.7	3.0
Cape Egmont	1.7	3.1	4.7	3.3	1.5	4.8
West Point	1.6	2.1	3.7	2.8	1.4	4.1
Miminegash	2.5	1.4	3.9	0.4	0.1	0.4
Nova Scotia						
Port Hood	2.1	2.4	4.5	-0.4	-0.4	-0.8
Auld Cove	2.2	2.5	4.7	-0.2	0.1	-0.1
Ballantyne Cove	2.1	2.7	4.8	-0.1	0.1	0
Arisaig	2.4	3.2	5.5	-0.2	-0.2	-0.4
Merigomish	2.5	3.1	5.6	-0.3	0	-0.3
Pictou Island	2.6	3.5	6.1	0.5	0.3	0.8
Pictou Harbour	2.6	3.3	5.9	0.2	0.2	0.4
Caribou Harbour	2.8	3.3	6.0	0.3	0.6	0.8
Skinners Cove	3.1	4.1	7.2	0.7	0.5	1.2
Malagash	3.6	4.1	7.7	0.8	1.4	2.2
Cape Cliff	3.3	4.7	8.0	2.0	1.5	3.5
Pugwash	3.7	5.1	8.8	1.8	1.3	3.1
Tidnish Head	3.8	5.2	9.0	1.6	1.3	2.8
New Brunswick						
Port Elgin	3.9	5.3	9.2	1.7	1.1	2.8
Tormentine (east)	3.1	4.5	7.6	2.3	2.0	4.3
Tormentine (west)	3.1	4.5	7.6	2.4	0.5	2.9
Cape Bald	1.6	3.0	4.6	3.6	1.6	5.2
Pointe du Chene	1.4	2.9	4.3	3.4	1.3	4.7
Caissie Point	1.4	2.7	4.0	3.5	1.6	5.1
Crossman Point	1.3	1.8	3.1	3.1	1.9	5.0
Richibucto Bar	2.2	1.5	3.7	1.1	1.1	2.2
Point Sapin	2.5	1.7	4.2	0.7	0.7	1.3

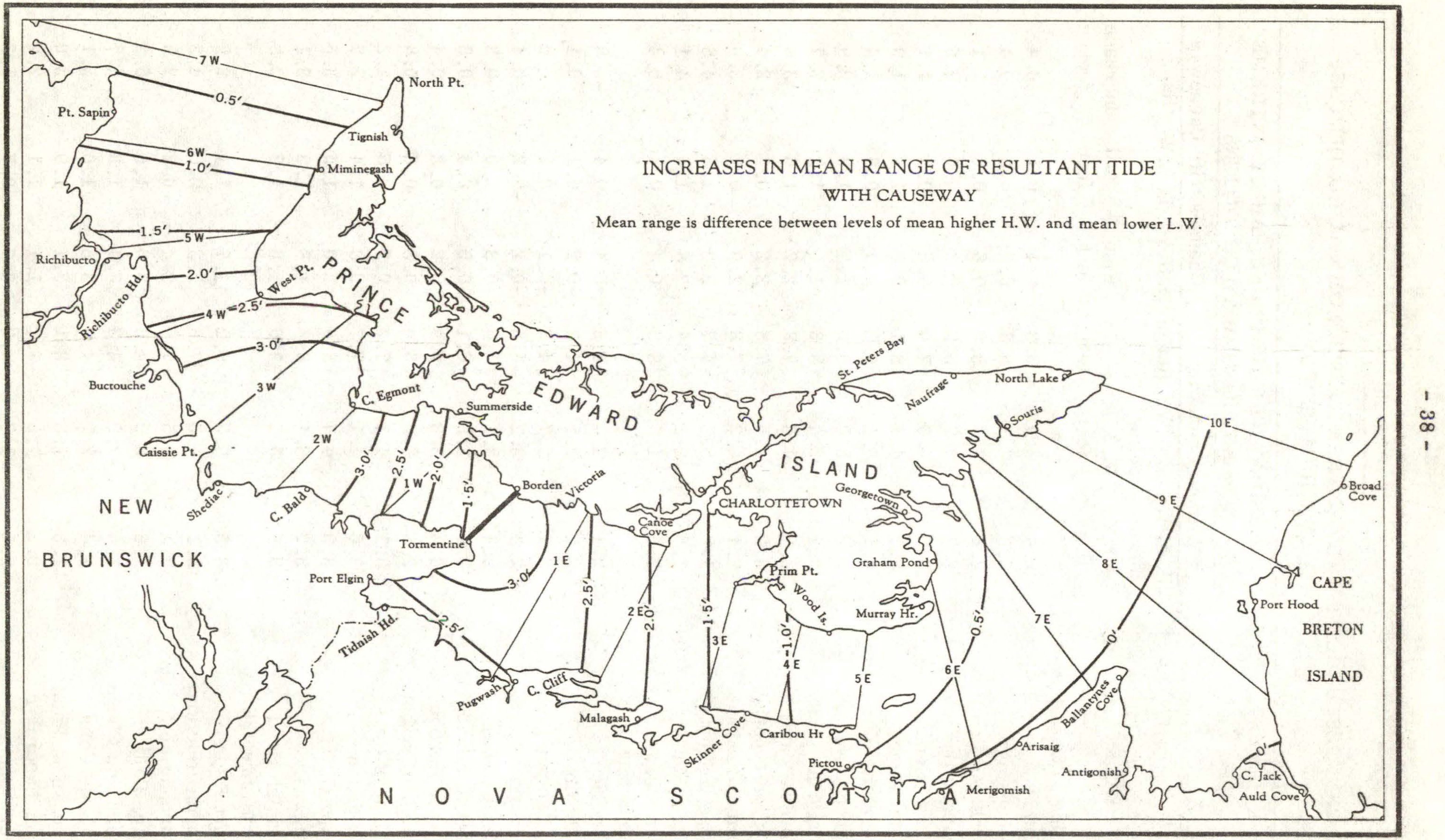

INCREASES IN MEAN RANGE OF RESULTANT TIDE
WITH CAUSEWAY
Mean range is difference between levels of mean higher H.W. and mean lower L.W.
PRINCE
EDWARD
ISLAND
NEW
BRUNSWICK
NOVA SCOTIA
CAPE
BRETON
ISLAND
North Pt.
Pt. Sapin
Tignish
Miminegash
Richibucto
Richibucto Hd.
West Pt.
Buctouche
C. Egmont
Summerside
Caissie Pt.
Shediac
C. Bald
Borden
Victoria
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Canoe Cove
CHARLOTTETOWN
Prim Pt.
Wood Is.
Skinner Cove
Caribou Hr
Pictou
Georgetown
Graham Pond
Murray Hr.
St. Peters Bay
Naufrage
North Lake
Souris
Broad Cove
Port Hood
Ballantynes Cove
Arisaig
Antigonish
Merigomish
C. Jack
Auld Cove
7 W
6W
5 W
4 W
3 W
2 W
1 W
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E
0.5′
1.0′
1.5′
2.0′
2.5′
3.0′

Fig. 3g.

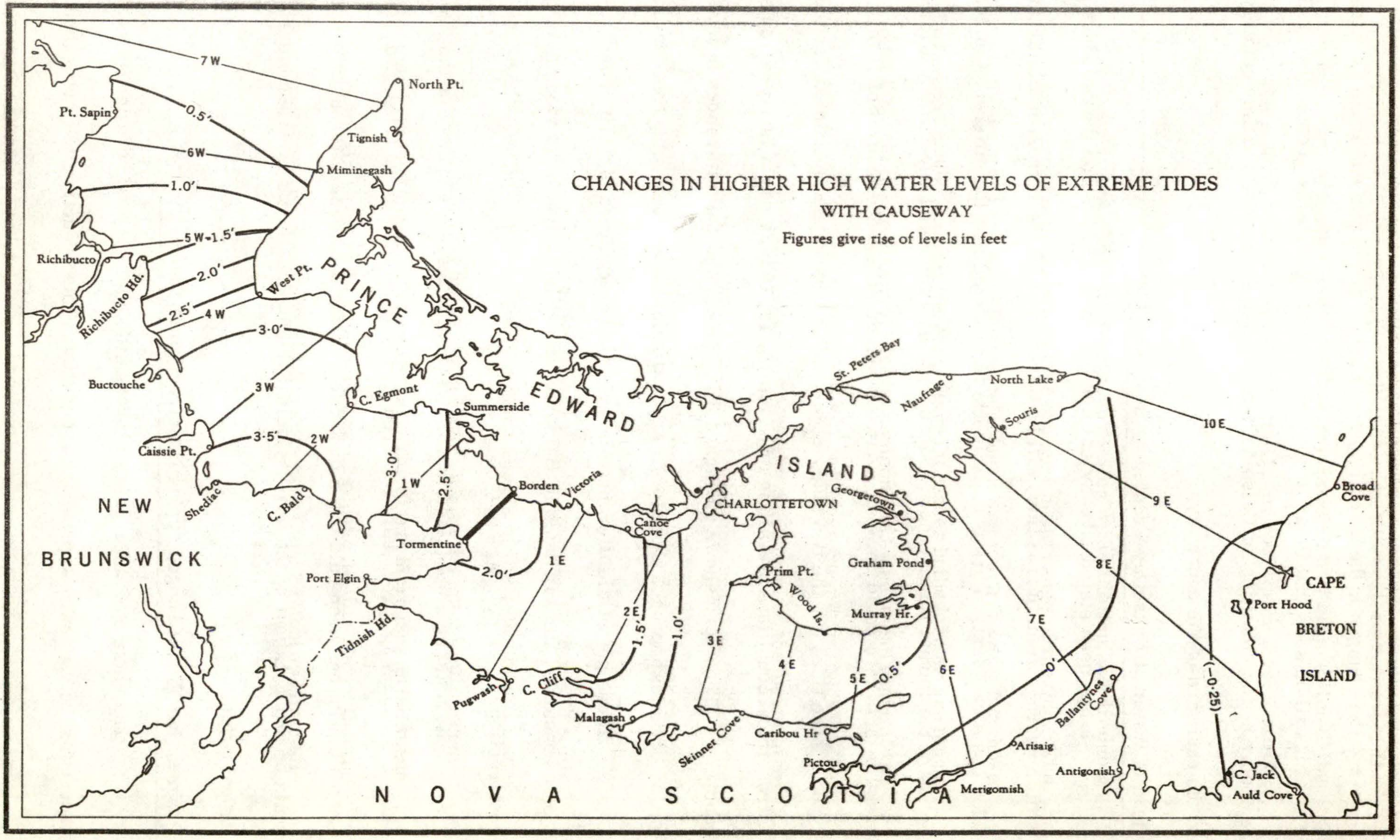

CHANGES IN HIGHER HIGH WATER LEVELS OF EXTREME TIDES
WITH CAUSEWAY
Figures give rise of levels in feet
PRINCE
EDWARD
ISLAND
NEW
BRUNSWICK
NOVA SCOTIA
CAPE
BRETON
ISLAND
North Pt.
Tignish
Miminegash
Pt. Sapin
Richibucto
Richibucto Hd.
West Pt.
Buctouche
C. Egmont
Summerside
Caissie Pt.
Shediac
C. Bald
Borden
Victoria
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Canoe Cove
CHARLOTTETOWN
Georgetown
St. Peters Bay
Naufrage
North Lake
Souris
Broad Cove
Graham Pond
Prim Pt.
Wood Is.
Murray Hr.
Skinner Cove
Caribou Hr
Pictou
Merigomish
Arisaig
Ballantynes Cove
Antigonish
Port Hood
C. Jack
Auld Cove
7 W
6W
5 W
4 W
3 W
2 W
1 W
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E
0.5'
1.0'
1.5'
2.0'
2.5'
3·0'
3·5'
0'
(—0·25)

Fig. 3h.

The changes in the lower low-water levels are shown on Figure 3i, page 41, and it will be seen that these levels are lowered by amounts greater than 1.5 feet only in the vicinities of Caissie Point and Cape Egmont, and immediately to the eastward of the causeway.

Head of Water at Causeway Created by Resultant Tide

It has been stated already that the differences in level on the two sides, with an average semidiurnal tide, will be 6 feet and with the largest semidiurnal tides could be 9 feet. Furthermore it has been stated that the difference in the levels of the diurnal tide on the two sides could be as much as one foot. It is thus possible that there could be, once a day a resultant difference in level of 10 feet.

The tides on the two sides of a causeway have been predicted for the astronomical conditions prevailing on November 13, 1958, a day of fairly extreme conditions. These are shown on Figure 3j, page 42, and the differences in level on this occasion approach those to be expected under the most extreme conditions.

These potential differences in level can be predicted directly from harmonic constants, for any dates in the future when they might be of value during construction.

It should be emphasised that the various differences in level on the two sides of a causeway, previously referred to, are solely due to the tides. Hitherto no attention has been paid to the probable increases in those differences which could be brought about by the non-periodical fluctuations in sea level of meteorological origin.

Progressive Tidal Changes during Construction of Causeway

The volume of water passing through the narrows will be progressively reduced as the causeway approaches completion. This reduction will bring about

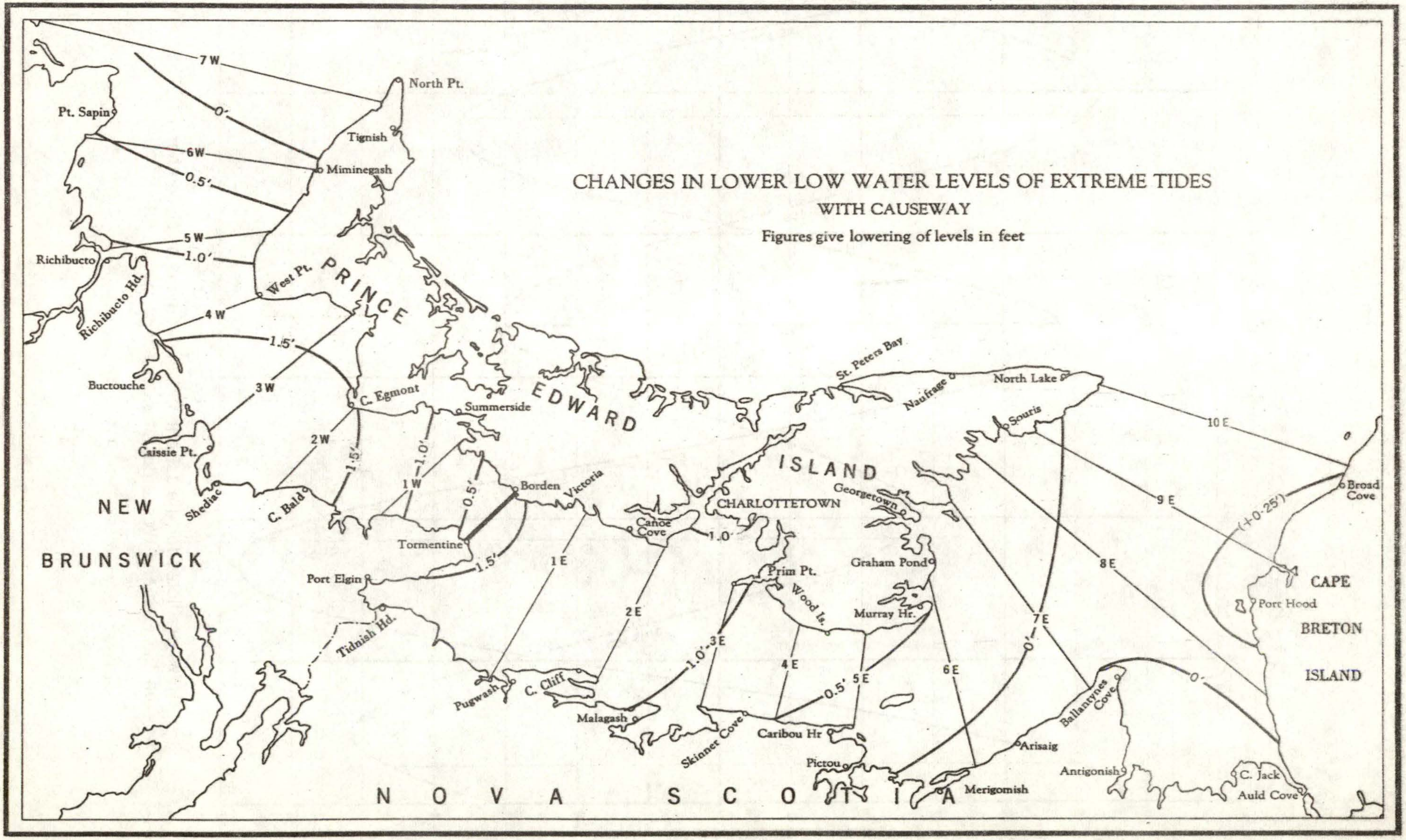

CHANGES IN LOWER LOW WATER LEVELS OF EXTREME TIDES
WITH CAUSEWAY
Figures give lowering of levels in feet
PRINCE
EDWARD
ISLAND
NEW
BRUNSWICK
NOVA SCOTIA
CAPE
BRETON
ISLAND
CHARLOTTETOWN
North Pt.
Tignish
Miminegash
Pt. Sapin
Richibucto
Richibucto Hd.
West Pt.
Buctouche
Caissie Pt.
Shediac
C. Bald
C. Egmont
Summerside
Borden
Victoria
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
Malagash
Canoe Cove
Prim Pt.
Wood Is.
Skinner Cove
Caribou Hr
Pictou
Merigomish
Arisaig
Ballantynes Cove
Antigonish
C. Jack
Auld Cove
Port Hood
Broad Cove
Georgetown
Graham Pond
Murray Hr.
St. Peters Bay
Naufrage
North Lake
Souris
7 W
6 W
5 W
4 W
3 W
2 W
1 W
1 E
2 E
3 E
4 E
5 E
6 E
7 E
8 E
9 E
10 E
0'
0.5'
1.0'
1.5'
(+0·25')

Fig. 3i.

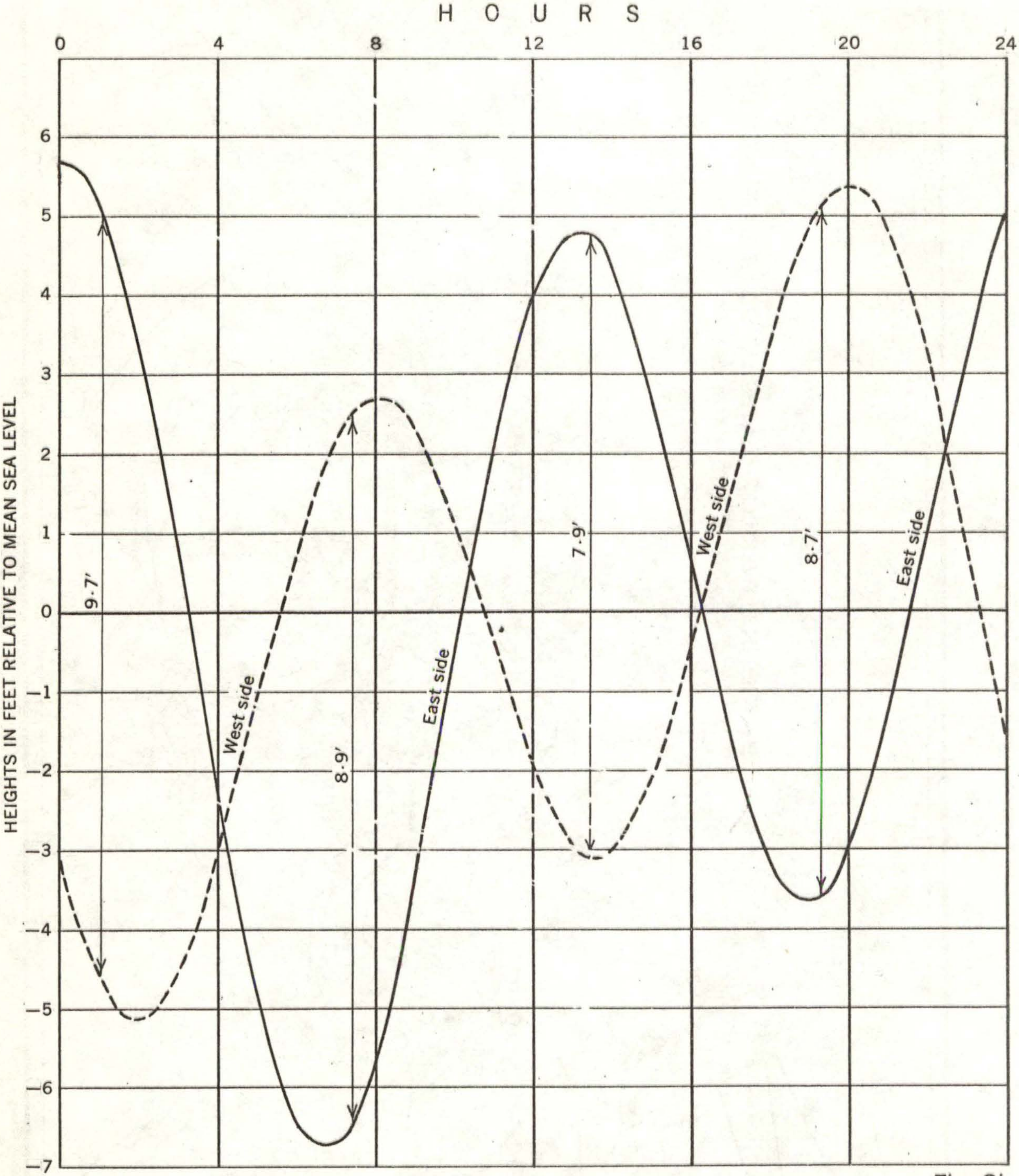


Fig. 3j.

Tides predicted for the astronomical conditions on November 13 1958 on the East and West sides of a causeway.

changes in tidal conditions in the western part of the Strait. The various stages by which the final change will be reached have been under discussion. As stated in Appendix B2, the Tidal Institute is unable to provide a satisfactory solution.

It would seem, when the causeway has reached an advanced stage, that a point must be reached when tidal conditions will approximate a mean between those now existing and those forecast when the barrier is complete. Figure 3k, page 44, shows the levels of the tidal constituent M_2 through the Strait, with and without a causeway, at simultaneous times. This time is close to high water at the site of the causeway prior to construction and also to high water on the east side and low water on the west side after construction. The firm line shows the levels prior to construction, with the amphidromic point at A. The dotted line shows an intermediate stage when the causeway is not yet complete, it suggests that the amphidromic point will retreat eastwards towards the causeway and disappear, and that at its original site the range will be small. The view of the Tidal Institute is that the extinction of the amphidromic point will occur quickly once construction has reached a certain stage.

SYNCHRONOUS LEVELS IN NORTHUMBERLAND STRAIT

At about time of High Water on eastern side of causeway site

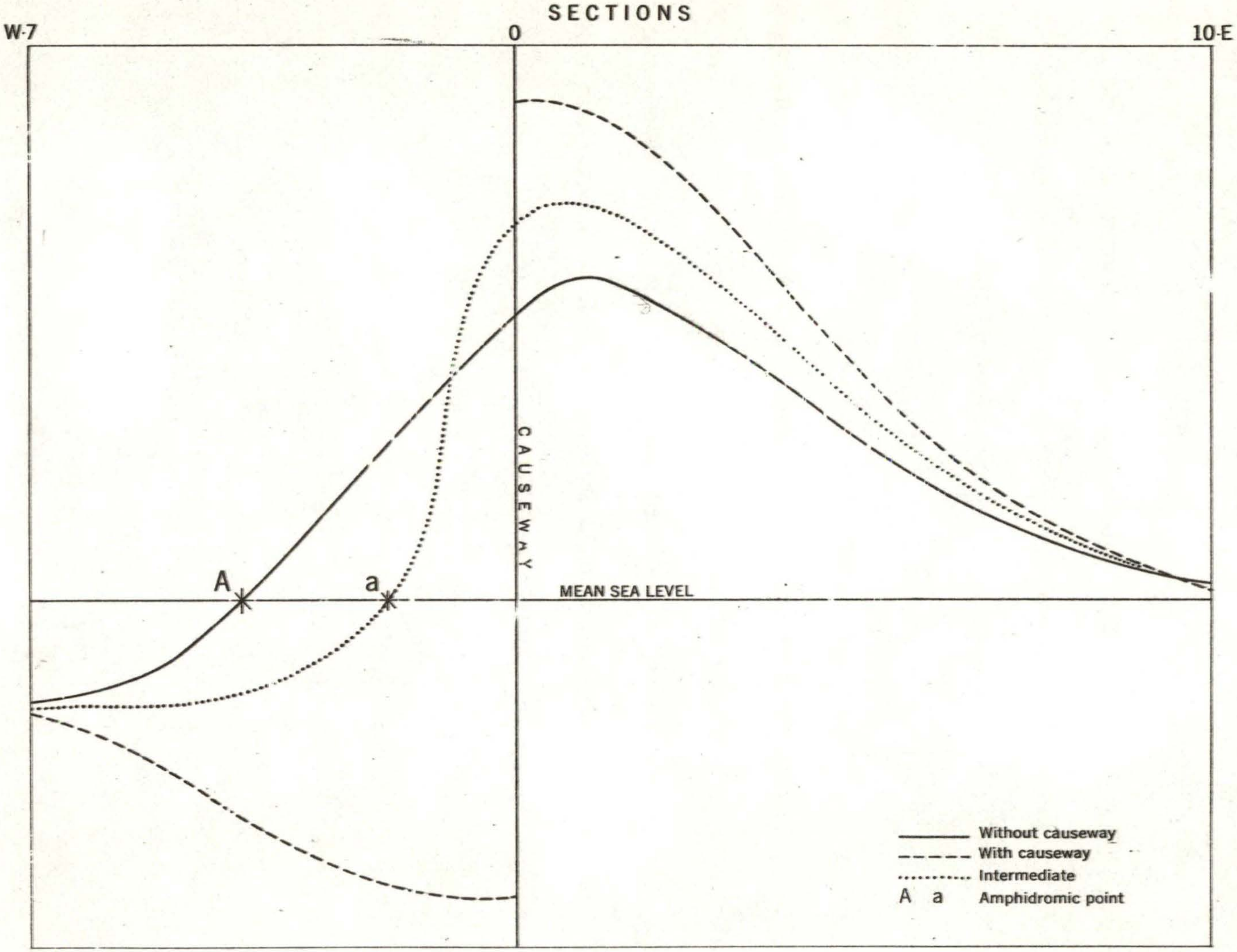


Fig. 3k.

4. NON-PERIODIC FLUCTUATIONS IN SEA LEVEL

The records from Northumberland Strait, at the tide gauges at present in operation and at those operated earlier during the past fifty years, have been examined with a view to ascertaining the following:

A The frequency with which very high levels have occurred, and to what extent such levels would be affected by the construction of a causeway.

B Whether the non-periodic fluctuations in sea level could temporarily increase the head of water at the causeway, by having different, or even opposite effects, upon the levels on the two sides.

The non-periodic fluctuations have been classified in the opening article as seiches, storm surges and secular changes in sea level. The first would have some bearing on B, storm surges - which are by far the most pronounced of these fluctuations - affect both A and B, while secular changes can only have a very long-term effect upon the frequency with which very high levels occur.

Seiches

At all ports on the Atlantic coast, small seiches, with amplitudes of only a few inches, occur almost continuously. These, however, only occur inside the Gulf of St. Lawrence over a limited distance from Cabot Strait and the Strait of Belle Isle. They are experienced in the eastern and western entrances to Northumberland Strait but become less and less conspicuous as the central part of the Strait is approached.

Occasionally seiches of much larger amplitude occur in these regions, but, prior to the present survey, there have never been sufficient gauges, simultaneously in operation, to trace the progress or decay of such a seiche.

In June 1958 a seiche was recorded at all the gauges in operation in the eastern entrance to Northumberland Strait. At some ports there, the seiche was noted and commented upon by the local fishermen, and was said by them to be the largest that had occurred for many years. The records from some of these gauges are reproduced on Figure 4a, page 47. The seiche at Broad Cove is typical of those which occurred in the entrance to the Strait, where the maximum fluctuation amounted to 2.2 feet, in a period of less than five minutes. However, towards the centre of the Strait these fluctuations rapidly died out and were not perceptible at Charlottetown.

No marked seiches have been detected on the records for the past 50 years at Charlottetown, although an incident at Canoe Cove, recollected by a fisherman, certainly suggests that they may sometimes occur further up the Strait.

Near the western entrance small seiches are quite frequent, but within this part of the Strait they are rarely noticeable. The most conspicuous which occurred there during the summer of 1958 is shown on Figure 4b, page 48. Even at Point Sapin in the entrance to the Strait, the maximum fluctuation of this seiche was less than a foot and at Caissie Point it was no longer of much significance.

Although there are no continuous records over a long period of years at any place in the vicinity of the site of the proposed causeway, there are records obtained only during the summer months at several places, and at some of them for two or three successive years. These records have been examined and no seiche of any importance was detected.

The evidence, from the occurrences in 1958 and from the past records, seems fairly conclusive that no seiches of any great magnitude are to be expected at the site of the proposed causeway.

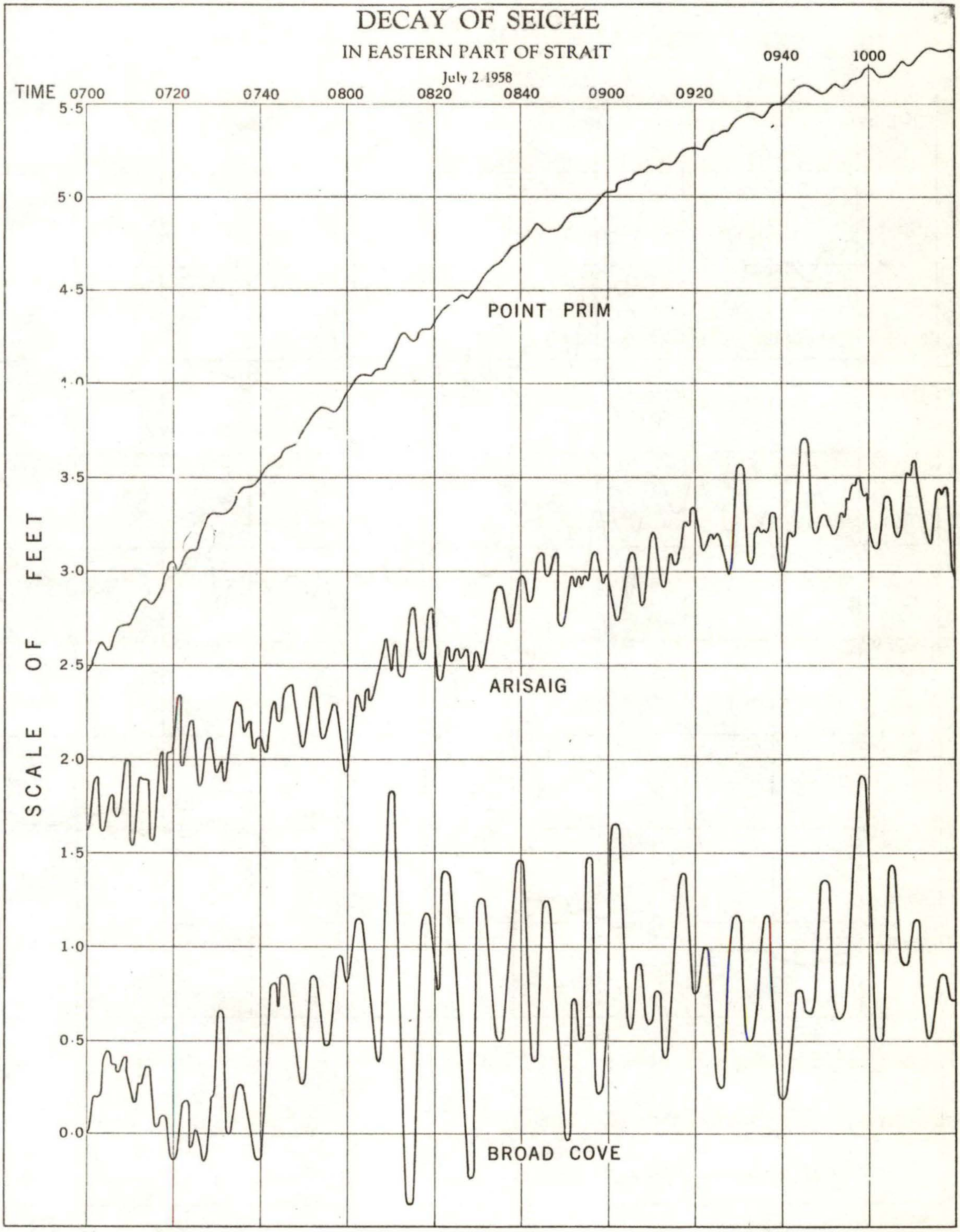

DECAY OF SEICHE
IN EASTERN PART OF STRAIT
July 2 1958
TIME 0700 0720 0740 0800 0820 0840 0900 0920 0940 1000
5·5
5·0
4·5
4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0·0
SCALE OF FEET
POINT PRIM
ARISAIG
BROAD COVE

Fig. 4a.

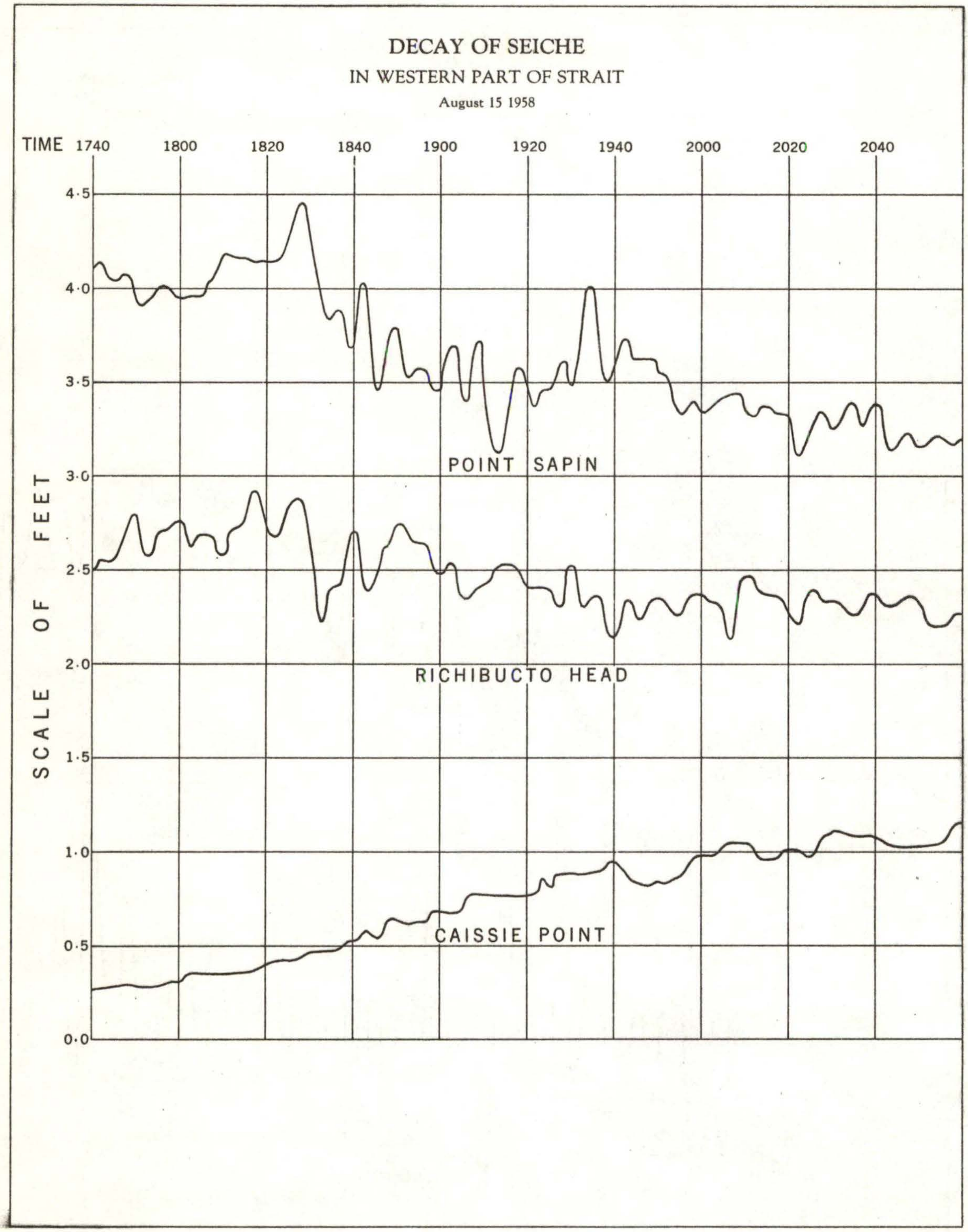

DECAY OF SEICHE
IN WESTERN PART OF STRAIT
August 15 1958
TIME 1740 1800 1820 1840 1900 1920 1940 2000 2020 2040
4·5
4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0·0
SCALE OF FEET
POINT SAPIN
RICHIBUCTO HEAD
CAISSIE POINT

Fig. 4b.

Storm Surges and Secular Changes in Sea Level

Storm surges are large fluctuations in sea level generated by gale-force winds and the associated changes in barometric pressure. They alternately raise and lower sea level in the Gulf by amounts of 4 feet or more, in a period, between successive high levels, of 1 to 1 1/2 days. The fluctuations gradually die out with the cessation of the gale, but, if a succession of deep depressions passes near the Gulf, the sea level may continue disturbed for perhaps as long as ten days.

Storm surges are entirely independent of astronomical conditions, thus they may occur anywhere between spring and neap tides, and their peaks and troughs may arrive at any state of tide between high and low water. The sea can rise to such a high level that disastrous floods occur, only however, if an exceptionally severe gale occurs at a time of very large spring tides and then only if the arrival of the peak of the surge generated by that gale coincides with high water of the tide.

Geodetic datum is a standard mean level of the sea, accepted at some time in the past as being the true mean at that particular time. The actual mean level of the sea may in later years become permanently altered by the secular changes, and at any time may be temporarily altered by storm surges. The tides oscillate above and below the average level of the sea at the time and if that mean is premanently or temporarily raised or lowered, then both the high water levels and the low water levels will be raised, or lowered, by the change in mean level. Very large tides at Charlottetown rise to 4.1 feet above Geodetic Datum and storm surges in Northumberland Strait may temporarily raise sea level by more than 4 feet. It follows that, if ever the worst possible combination of tide and surge occurs, the sea will rise to a level of more than 8 feet above Geodetic Datum.

Actually, over a period of 50 years, the highest recorded level is only 6.6 feet above Geodetic Datum. As surges are a quite common occurrence during the winter months, it is evident that the chances of a really adverse combination of tide and surge are remote. This is further illustrated by events elsewhere, for the combination which resulted in the disastrous floods on the shores of the North Sea in 1953, while not the worst possible, was far worse than any recorded for several centuries previously, and in the Bay of Fundy, the "Saxby Tide" of October 1869 reached levels never approached since.

The Tidal Survey was asked to undertake a frequency analysis of the occurrence of very high levels in Northumberland Strait. It is, however, only at Charlottetown that continuous observations have been obtained for a long enough period to justify such an analysis. Any conclusions drawn from this analysis should be applicable also to the area south of Hillsborough Bay extending to Cape Tormentine, for in it the times of high water and the range of the tide do not differ greatly from those at Charlottetown. A confirmation of this assumption rests on the evidence that a large storm surge which occurred in November 1918 raised the sea at Charlottetown and at Borden above the highest tidal levels by the same amount of 2.3 feet.

A frequency analysis of very high levels at Charlottetown is complicated by the fact that over the last 30 years there has been a rise of 0.5 feet in the mean level of the sea which is now appreciably higher than the Standard Mean Sea Level adopted as Geodetic Datum, which in 1945 was the long-term mean. For analysis, it has been assumed that the tide alone cannot rise over a level of 4.1 feet above Geodetic Datum, and that there must have been contributions from both tide and surge when any higher level was reached. With the rise in mean sea level this is no longer true.

The analysis covers a period of about 50 years and 36,000 tides; the lower curve on Figure 4c, page 53, shows the number of tides per 1,000 which have reached the levels, shown on the height scale, between 4.1 and 6.6 feet above the Standard M. S. L. As 1,000 tides occur in a period of about 16 months, the frequency can be converted to a monthly or annual reference.

Figure 4d shows the annual values of mean sea level during the past 50 years at Charlottetown. These fluctuate from year to year by amounts which are rarely more than ± 0.1 feet from a 5-year mean. Such fluctuations are to be expected from annual variations in mean weather conditions. A progressive change in climatic conditions, which affects the volume of water imprisoned in the polar ice caps, will lead to a change in the level of the sea, relative to that of the land. A rise in sea level, similar to that at Charlottetown, is evident at all the ports on the Atlantic coast. This rise is naturally reflected in the annual number of occasions when the level of 4.1 feet above Standard M. S. L. is exceeded; these are shown by the upper curve on Figure 4c. This number shows a marked and fairly progressive increase since 1935.

The frequency curve, being based on the heights recorded in the 50-year period relative to a fixed datum plane, does not take into account the rise in sea level and therefore does not represent present-day conditions.

The present frequency can be more accurately assessed by allowing for the difference of 0.3 feet between the average value in the 50-year period, and the final value, of Mean Sea Level. Thus, in order to find the present frequency of the occurrence of heights of 4.9 feet above standard M. S. L. the height scale reading used should be (4.9 - 0.3) feet, or 4.6 feet. This will give a frequency of 10 per 1,000 tides, instead of 4 per 1,000 for the 50-year period.

Table 4, page 52, shows a list of places in Northumberland Strait, where

TABLE 4

FREQUENCY OF VERY HIGH LEVELS WITHOUT CAUSEWAY

(for sea level in 1958)

Freq. per 1000 tides	Heights in feet above Chart Datum						
	Charlotte-town	Victoria	Borden	Cape Tormentine	Port Elgin	Pugwash	Malagash
1	10.6	11.5	9.4	9.7	10.6	10.0	10.0
3	10.2	11.1	9.0	9.3	10.2	9.6	9.6
10	9.8	10.7	8.6	8.9	9.8	9.2	9.2
32	9.4	10.3	8.2	8.5	9.4	8.8	8.8

Chart datum at these ports is at the following levels:

Charlottetown	18.38 feet below an inverted broad arrow cut on top of sandstone plinth on brick block at southwest corner on Queen and King Streets.
Victoria	30.78 feet below a bronze tablet "B. M. 1943" set horizontally in concrete foundation of Bank of Nova Scotia, 2 feet east of southwest corner and 1 foot below sill.
Borden	38.32 feet below B. M. No. 1, Railway steel water tank, southwesterly concrete footing, southeast corner of surface of steel bedplate, in front of name plate.
Cape Tormentine	17.73 feet below B. M. No. 1, "Seaside" Hotel, northeast foundation wall, in top course at 22' 9" from rear corner, 4" below woodwork.
Port Elgin	17.71 feet below B. M., stamped TS-1, 1958, on south concrete foundation wall of railway station, one foot from southwest corner and one foot below brickwork.
Pugwash	23.16 feet below B. M. No. 2, on railway bridge over river, concrete guard block at the north end, in the middle of the top surface of the block.
Malagash	27.58 feet below a broad arrow, cut in stone foundation of United Church on south side, 4 1/2 feet from west corner, 4" below siding.

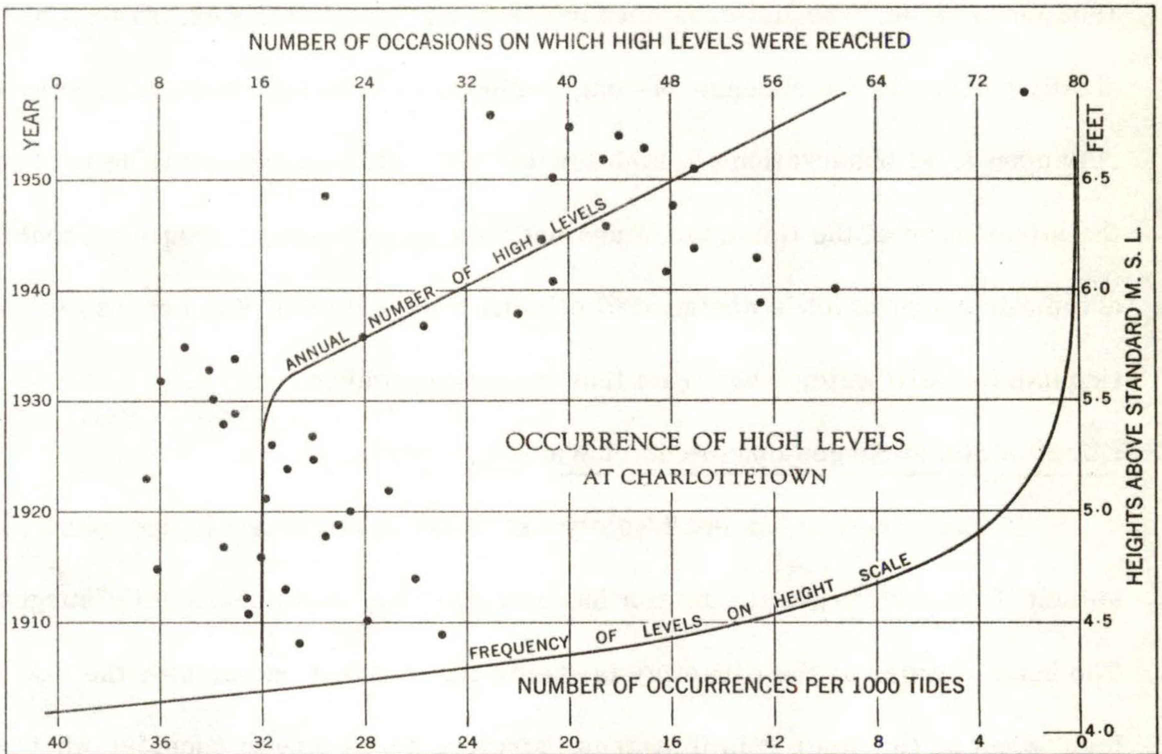

NUMBER OF OCCASIONS ON WHICH HIGH LEVELS WERE REACHED
0
8
16
24
32
40
48
56
64
72
80
YEAR
1950
1940
1930
1920
1910
ANNUAL NUMBER OF HIGH LEVELS
OCCURRENCE OF HIGH LEVELS
AT CHARLOTTETOWN
FREQUENCY OF LEVELS ON HEIGHT SCALE
NUMBER OF OCCURRENCES PER 1000 TIDES
40
36
32
28
24
20
16
12
8
4
0
FEET
6·5
6·0
5·5
5·0
4·5
4·0
HEIGHTS ABOVE STANDARD M. S. L.

Fig. 4d.

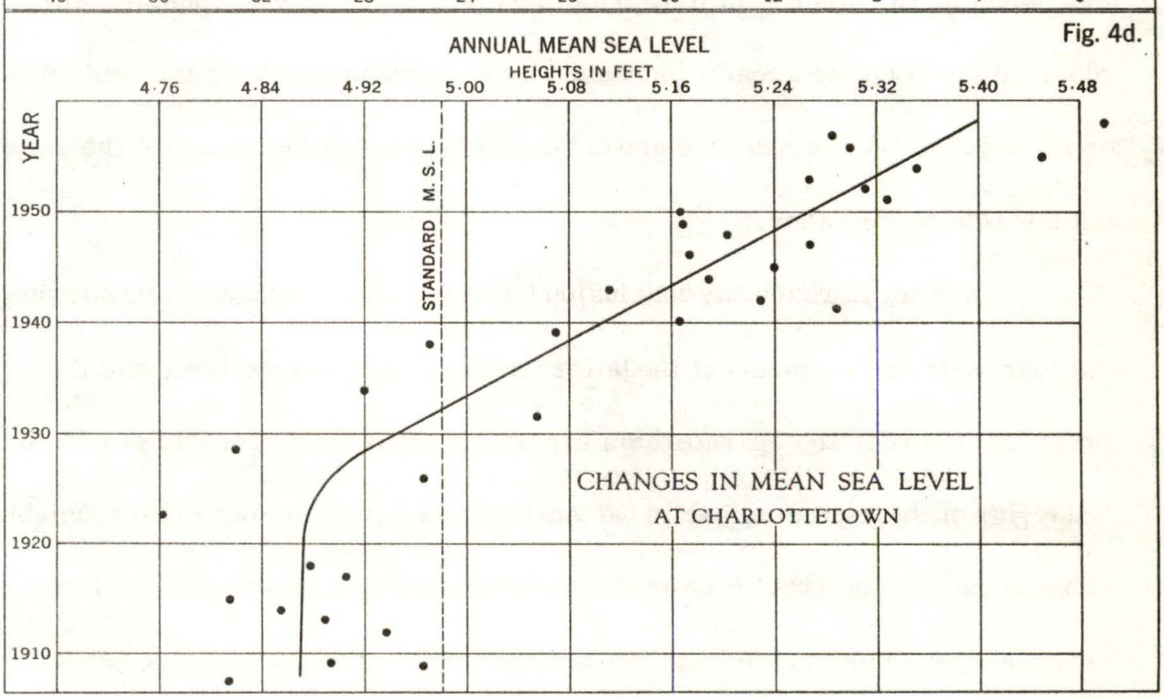

ANNUAL MEAN SEA LEVEL
HEIGHTS IN FEET
4·76
4·84
4·92
5·00
5·08
5·16
5·24
5·32
5·40
5·48
YEAR
1950
1940
1930
1920
1910
STANDARD M. S. L.
CHANGES IN MEAN SEA LEVEL
AT CHARLOTTETOWN

Fig. 4c.

the frequency of high levels can be expected to correspond fairly closely with that at Charlottetown. It gives for these places the frequency with which certain levels above chart datum may be expected to occur, with sea level at about its 1958 mean value. The list does not include any places in the western part of the Strait, where, in the absence of long-period observations, it is necessary to rely upon local observations of high levels. It would also be advisable to check the information at the listed ports against local experience, although without an automatic gauge which is designed to eliminate wave action, it is not easy to distinguish the still water level from that reached by waves.

Effect of Storm Surges upon Head of Water at Causeway

The foregoing has dealt solely with the high-water levels due to the resultant of tide and surge, so attention has been paid only to the peaks of the surges. The head of water at the causeway is due to the fact that on one side the tide is high, when on the other it is low. It is therefore necessary to consider whether this head could not be greatly increased by coincidence between the peak of the surge and high tide on one side and coincidence between the trough of the surge and low tide on the other.

In order to reach any conclusion it is essential to separate tide and surge and to trace the development of the latter as it travels along the coast and through the Strait. In order to separate them at any port, it is first necessary to predict the heights of the astronomical tide at that port and then to compare these heights with the observed heights which are the resultant of astronomical tide and meteorological surge. For the study of the development of the surge, it is essential to have a network of tidal stations at which such comparisons may be made. Prior to the present survey, no such network had ever been maintained, and in consequence there is no back-log of data which are necessary for this type of research.

It must be borne in mind that the sequence of meteorological changes, which give rise to surges, is not exactly repeated and so the development of surges, although there are many features in common, does not follow a rigid pattern. In consequence, the study of only a few local surges may result in misleading conclusions.

In contrast to those in the North Sea, storm surges in Canadian waters are not a menace to life and property, and the need for intensive study, as undertaken by countries bordering the North Sea, has never arisen. That sea has a wide and deep northern entrance opening onto the North Atlantic Ocean, and storm surges are generated by gale-force winds from a northwesterly direction experienced behind the centre of a deep depression. Water is driven southwards, and an increasingly high elevation is built up as the surge reaches the more restricted area in the southern part of the Sea. In Canada, similar conditions but to a lesser degree, are likely to occur in James Bay, following the passage of deep depressions across the northern part of Hudson Bay.

Geographically, the Gulf of St. Lawrence is quite different; the northern part of the Gulf and the Strait of Belle Isle are narrow whereas the cross-section of the Gulf increases in the southern part. In consequence, the volume of water that can be transported southwards from the northern part of the Gulf, and from outside the Gulf through the Strait of Belle Isle is very small in relation to the cross-section of the southern end. Any large influx of water must enter the Gulf through Cabot Strait, and be impelled through the Strait by the easterly, or south-easterly, winds which precede the arrival of the centre of the depression.

The first surge, which occurred after the network of gauges was established, was that generated by hurricane Helene, which passed northwards off the coast of Nova Scotia. With its approach, at 0000 on September 29, the winds in Cabot Strait were easterly, becoming increasingly strong until the centre had passed. By about 1200 there had been an abrupt change to equally strong winds from a westerly direction. The abrupt change, from conditions where the wind and the barometric pressure strongly favoured a rise in the sea level, to those with the reverse tendency, is ideal for setting up an oscillation in sea level, which continues long after the generating forces have ceased. In the western half of the Gulf, the winds were northeasterly early on September 29, gradually turning through north to become northwesterly after the passage of the hurricane. These early winds from the northeast may have caused a small increase in sea level in the western part of the Gulf, prior to the arrival of the main surge.

This surge is illustrated on Figures 4e, 4f, and 4g, pages 57, 58 and 59 respectively. These show the oscillations in sea level (observed-predicted heights) due to the changes in meteorological conditions for the period September 28 to October 1. At Harrington in the northern part of the Gulf and at Port Hastings on the Atlantic coast of Nova Scotia, the surge was comparatively insignificant. At the latter and at North Sydney the changes in elevation are very irregular owing to the action of seiches.

In Cabot Strait and in the eastern part of Northumberland Strait, the peak of the surge arrived between 0700 and 0900 on September 29, more or less coinciding with the passage of the centre of the depression, and sea level was raised by about 3 feet.

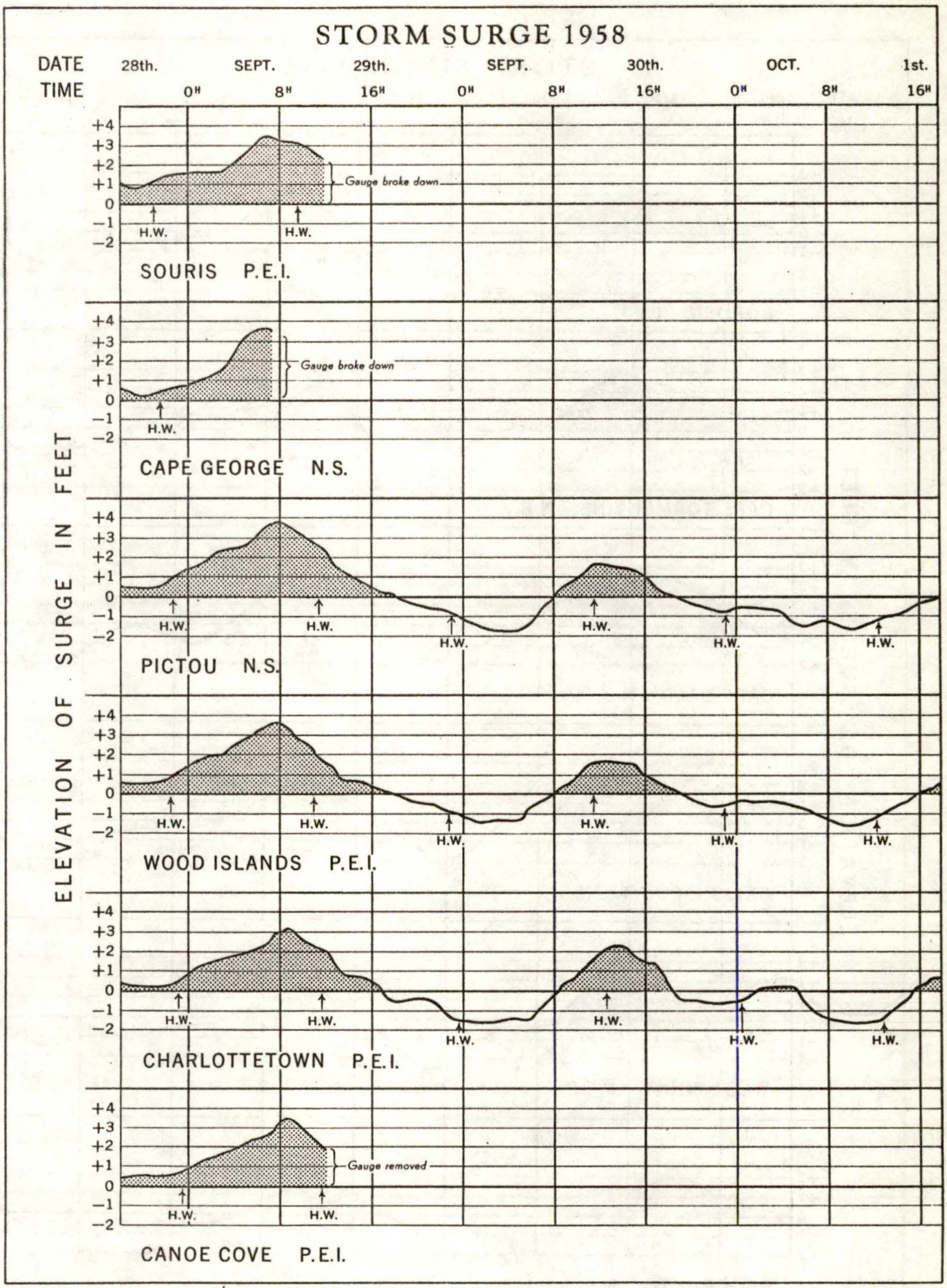

STORM SURGE 1958
DATE
TIME
28th.
SEPT.
29th.
SEPT.
30th.
OCT.
1st.
0H
8H
16H
ELEVATION OF SURGE IN FEET
+4
+3
+2
+1
0
−1
−2
H.W.
Gauge broke down
SOURIS P.E.I.
CAPE GEORGE N.S.
PICTOU N.S.
WOOD ISLANDS P.E.I.
CHARLOTTETOWN P.E.I.
Gauge removed
CANOE COVE P.E.I.

Fig. 4e.

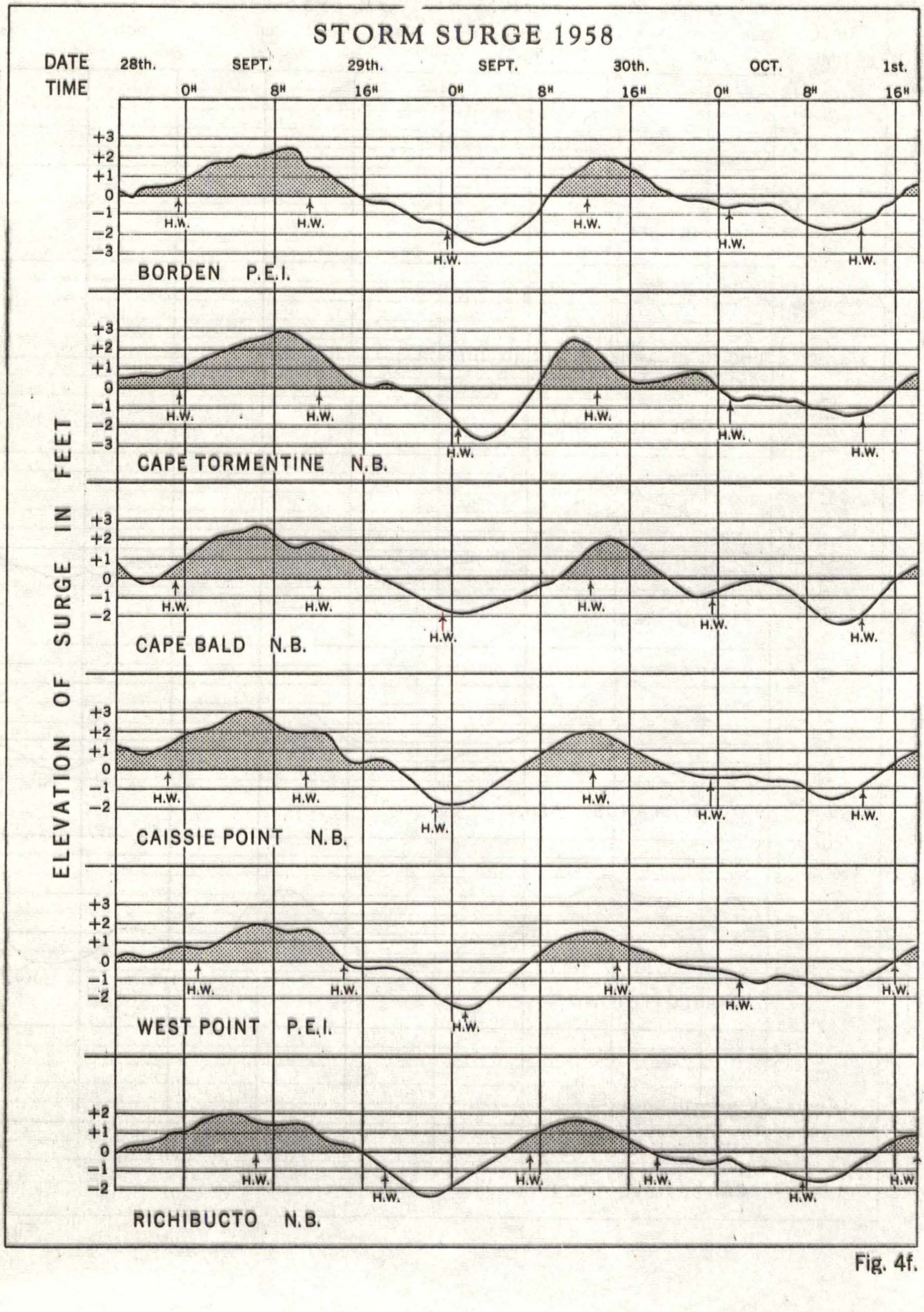

STORM SURGE 1958
DATE
TIME
28th.
SEPT.
29th.
SEPT.
30th.
OCT.
1st.
0H
8H
16H
ELEVATION OF SURGE IN FEET
+3
+2
+1
0
−1
−2
−3
H.W.
BORDEN P.E.I.
CAPE TORMENTINE N.B.
CAPE BALD N.B.
CAISSIE POINT N.B.
WEST POINT P.E.I.
RICHIBUCTO N.B.

Fig. 4f.

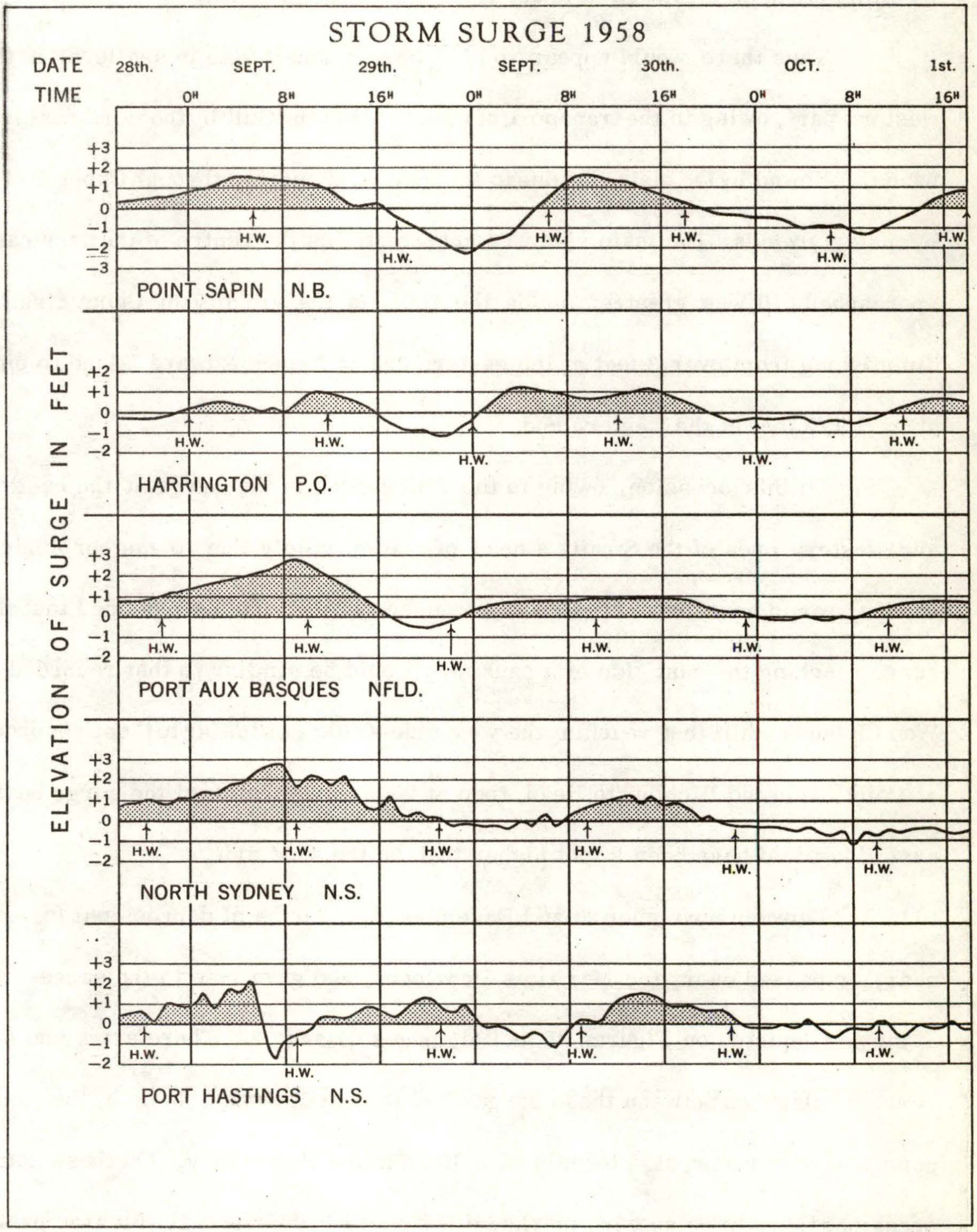

STORM SURGE 1958
DATE 28th. SEPT. 29th. SEPT. 30th. OCT. 1st.
TIME 0H 8H 16H 0H 8H 16H 0H 8H 16H
ELEVATION OF SURGE IN FEET
POINT SAPIN N.B.
HARRINGTON P.Q.
PORT AUX BASQUES NFLD.
NORTH SYDNEY N.S.
PORT HASTINGS N.S.
H.W.

Fig. 4g.

In the western entrance to Northumberland Strait, at Point Sapin and Richibucto Head, the peak of the surge arrived about 0400 and did not raise sea level by more than 2 feet. This was not followed by a steep fall but by a general levelling off to an elevation of about 1 1/2 feet by about 1000.

Thus there would appear to have been a small rise in sea level in the western part, owing to the transport of water inside the Gulf by the northeasterly winds, followed by the main rise due to the water transported through Cabot Strait by easterly winds. The main rise was accentuated as the centre of the hurricane approached. It was greatest inside the Gulf, in the vicinity of Cabot Strait, diminishing from over 3 feet at the eastern end of Prince Edward Island to only about 1 1/2 feet at the western end.

On this occasion, owing to the differences in the surge at the eastern and western ends of the Strait, a head of water, solely due to meteorological causes, would have been created at a causeway. If it can be assumed that the surge reaching the east side of a causeway would be similar to that recorded at Wood Islands while that reaching the west side would be similar to those recorded at Point Sapin and Richibucto Head, then at 0800 the elevation of the surge on the east side could have been 2 feet higher than on the west side.

Between November 28 and December 5, a series of depressions formed near, or passed over, the Maritime Provinces, and gave rise to the succession of surges depicted on Figures 4h and 4i, pages 61 and 62. There are some obvious similarities between these surges and the earlier ones. In both, the peaks nearly always recur at intervals of a little more than a day. On these later occasions there were no very marked differences in the times at which the peaks reach the eastern and western entrances to Northumberland Strait. As a general

STORM SURGE 1958

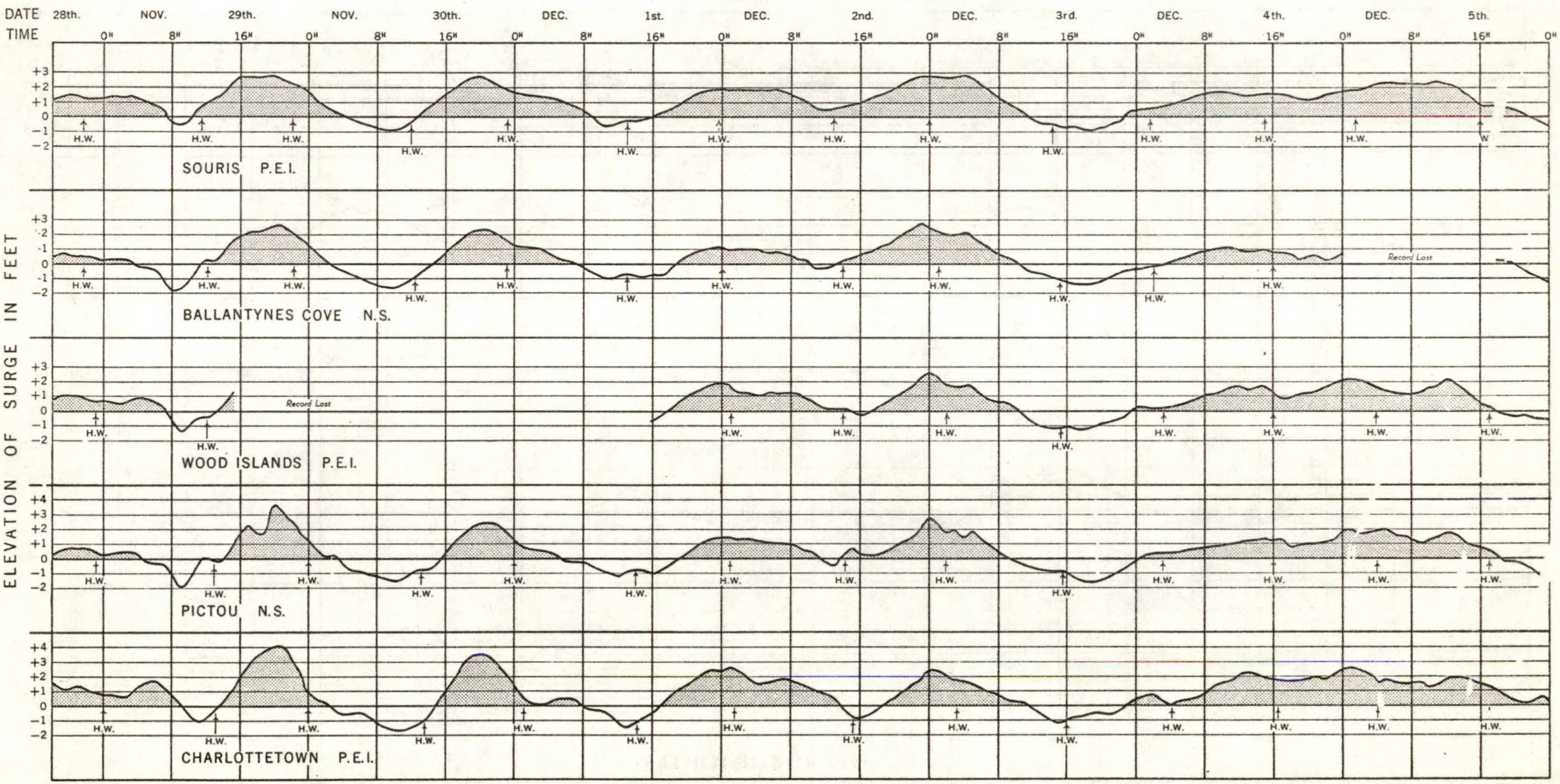


Fig. 4h.

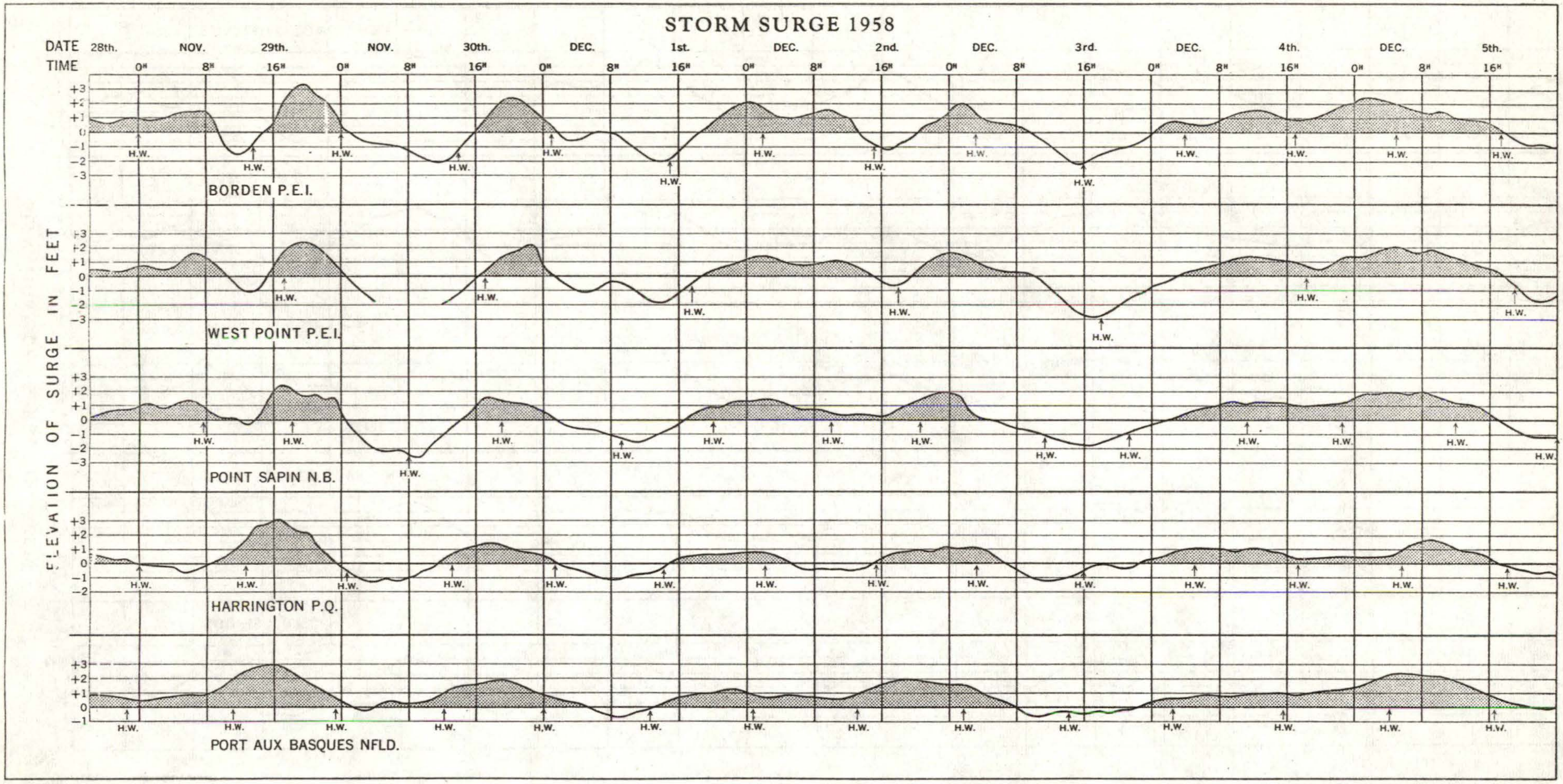

STORM SURGE 1958
DATE 28th. NOV. 29th. NOV. 30th. DEC. 1st. DEC. 2nd. DEC. 3rd. DEC. 4th. DEC. 5th.
TIME 0H 8H 16H 0H 8H 16H 0H 8H 16H 0H 8H 16H 0H 8H 16H 0H 8H 16H 0H 8H 16H
ELEVATION OF SURGE IN FEET
BORDEN P.E.I.
WEST POINT P.E.I.
POINT SAPIN N.B.
HARRINGTON P.Q.
PORT AUX BASQUES NFLD.
H.W.

Fig. 4 i.

rule the troughs of the oscillations fall lower in the latter entrance. A comparison between the elevations at Wood Islands and Ballantynes Cove in the eastern entrance and those at West Point and Point Sapin in the western entrance shows that, had a causeway been in existence at the time, the only occasion when the differences in surge elevation on the two sides might have been as great as 2 feet, was at about 0800 November 29, when the western side was the higher.

Investigations by Tidal Institute

At the commencement of the investigation, the Tidal Institute was asked to estimate the differences in level on the two sides of a causeway which could be created by strong winds blowing down the Strait. When the surge data became available, the Institute was asked to broaden the scope of the investigation, because it was felt that the effects of local winds, in creating a head of water at the causeway, could be offset to some extent by those blowing over the Gulf as a whole. The Institute's conclusions as to the meteorological effects upon sea level are included in Appendix B2, Appendix C, and a letter attached to Appendix C which is a reply to a request for a further explanation of some of the conclusions. Whereas the Institute reaches firm conclusions as to the effects of steady winds blowing down the Strait, it is emphatic that the available data are inadequate for a thorough investigation of the more complex problems. The points referred to in the Institute's reports have a bearing upon A. - the extent to which the occurrence of very high levels will be affected by the construction of a causeway, and B. - the extent to which meteorological disturbances of sea level could temporarily increase the head of water at a causeway. As the conclusions with regard to the latter are less speculative, they are summarised first.

B. -Strong winds blowing down the Strait would create large differences in level on the two sides of the causeway. The available data are inadequate for determining whether these effects of local winds would be modified by those blowing over the Gulf as a whole. It would be necessary to extend the existing network of tide gauges to a number of sites in the Gulf and thus obtain further data before this problem could be solved.

A. -Very strong winds blowing down the Strait could raise the level on one side of the causeway by as much as 5, or even 6, feet. Such elevations are rather greater than that reached by any surge at Charlottetown during the last 50 years. Thus, the causeway would create a new effect of meteorological conditions, which in its vicinity could cause higher levels than any to be expected under existing conditions. The Institute is of the opinion that there would be no appreciable magnification of a surge travelling up the Strait due to the existence of the causeway, but states that there is no theoretical method by which this could be determined.

Conclusions

So far as the creation of a head of water is concerned, it is clear that, should there be an adverse combination of tidal and meteorological conditions, there is risk of an extremely violent flow through the gap in a nearly completed causeway. The frequency analysis of very high levels at Charlottetown has shown that a very adverse combination of tidal and meteorological conditions is an extremely rare occurrence. The period during which the gap is narrow will be relatively short and it may be reasonable to regard a potential head of water of 12 feet as the worst to be anticipated during that short period.

In regard to the occurrences of very high levels, there are a number of points which should be considered. The static effects at the causeway of a strong wind blowing down the Strait, and the effects of a travelling surge which reaches the causeway, can be treated as related or as unrelated occurrences. If the two effects are created by the same storm, then there must be a risk that they will, to some degree, supplement each other on one side or other of the causeway and thus cause an elevation greater than is at present attained by a surge alone.

If, on the other hand, the two effects are created by different meteorological conditions, then the static effects will occur under circumstances when at present there would be no rise in sea level. Hence a greater frequency in the occurrence of very high levels will arise through a greater diversity of the meteorological conditions which cause them, and hence the chances of the occurrence of a more adverse combination of tidal and meteorological conditions than hitherto recorded.

There is a possibility, about which the Institute is non-committal, that the elevation of a travelling surge would be increased by reflection from the causeway. In view of the Institute's conclusion that currents of 2 knots could be associated with the progress of a surge, it is thought that this possible increase in elevation, by reflection at the causeway, should not be entirely ignored.

If the present trend for a rise in sea level continues - and during 1958 at Charlottetown and the Atlantic coast ports sea level was higher than ever before - the present very high levels must be reached more frequently, or exceeded, in the future.

The foregoing seem sufficient reasons for anticipating an increase of at least one foot in the meteorological effects upon sea level in the vicinity of the causeway.

Finally it might be as well to bear in mind that, after the construction of a causeway, any adverse combination of tide and surge will be generally attributed to its construction, although in fact such a combination is purely fortuitious.

5. RESIDUAL CURRENTS

Factors Limiting the Accuracy of Short-period Observations

In one, or more, exact tidal periods a particle of water solely under the influence of tidal streams will make no progressive movement; it simply travels to and fro either past, or in an ellipse around, a point which is stationary over the seabed. In analysing observations of the horizontal water movements, any progressive movement is attributed to residual current. Along the shores of the Gaspé Coast, for example, the residual current sets continuously seaward, fluctuating in rate with changes in meteorological conditions but constant in direction. It was not anticipated that there would be any pronounced residual current through Northumberland Strait, but it was hoped that observations continued over a period of 15 days, or so, would yield a reasonably reliable mean value for the residual current at the sites where the automatic meters were moored. Actually the current was found to fluctuate to such a degree that it is doubtful whether continuous observations for any period shorter than a month will yield a mean to which much weight could be attached.

The effects of abrupt changes in meteorological conditions upon the level of the sea have already been described in Section 4 under "Storm Surges". These surges are due to the temporary transport of water and must therefore be associated with non-periodic currents. Thus, the conditions which give rise to "storm surges" must also give rise to major fluctuations in the residual currents. In addition to these major effects of meteorological conditions, the analyses of the tidal records from the gauges in Northumberland Strait show that, even in the summer months, there are frequent, though usually small, non-tidal fluctuations in sea level. These too must be accompanied by fluctuations in the residual currents. In consequence the current at any site, as determined from observations over only a few tidal cycles, may bear little resemblance to the long-term mean.

Direct Observations by Automatic Current Meters

In the period between July 20 and September 21, 1958, one to three automatic meters were continuously in operation. The daily rates and directions of the residual currents at each site are given in Table 5a, facing. The sequence is chronological but the geographical positions of the various sites can be found from Figures 1a and 1b, pages 13 and 14. One of the two sites where really large residual currents were recorded was AB_1, which lies 7 miles southeastward from East Point, Prince Edward Island. Over the 24 days' observations, the mean set was quite strongly southwards into the Strait. Earlier in the season meters were in operation at site A_1, about 7 miles eastward from East Point and at B_1 about 14 miles southwestward. At the former, from 7 days' observations, the average set was southeasterly into the Strait. At B_1, from 13 days' observations, the rate was weaker and the direction was out of the Strait in a northerly direction. It would seem, therefore, that as a general rule there is an easterly residual current along the north shore of Prince Edward Island, which sets round East Point into the entrance to Northumberland Strait. The data from B_1 suggests that, close to the east coast of Prince Edward Island, part of this inset eddies northwards.

In the central part of the Strait, in the vicinity of the proposed causeway, where G_1, H_6, H_1, I_2 and J_2 were sited, no very strong residual currents were recorded. It is considered that the accuracy with which the residual current can be determined with the automatic meters is of the order $\pm$ 2 miles per day and approximately 50% of the recorded residual rates did not exceed this

TABLE 5a

RESIDUAL CURRENTS

DATE		SITE H1 r	d	H6 r	d	K5 r	d	F1 r	d	L1 r	d	J2 r	d
July	20	2	277°										
	21	3	246°										
	22	4	330°	3	187°								
	23	4	289°	2	181°								
	24	1	316°	1	193°								
	25	1	316°	1	033°								
	26	2	349°	3	311°								
	27	4	292°	3	298°								
	28	5	290°	2	309°								
	29	6	311°										
	30	4	240°										
	31	4	229°										
Aug.	1	2	251°										
	2	3	216°										
	3	2	240°										
	4	1	242°										
	5	3	253°										
	6	1	168°										
	7	1	269°			4	198°						
	8	1	006°			2	224°						
	9	6	131°			9	168°	14	141°				
	10	9	128°			8	172°	23	121°				
	11	6	125°			7	179°	17	140°				
	12	2	184°			6	152°	16	129°				
	13					3	155°	15	121°				
	14					5	155°	11	146°				
	15					4	155°	9	142°				
	16					0	335°	7	176°	0	050°		
	17					2	335°	4	271°	1	170°		
	18					1	335°	2	297°	1	345°		
	19					0	335°	5	104°	5	078°		
	20							6	103°	6	092°		
	21	MEAN		MEAN		MEAN		MEAN		7	081°		
	22									4	070°	0	--
	23	0.9	236°	0.3	264°	1.7	167°	9.6	136°	0	212°	0	125°
	24	AB1		G1		I2		K10		1	160°	1	125°
	25									3	070°	1	125°
	26									2	020°	0	305°
	27											1	305°
	28	5	202°									0	--
	29	3	212°									1	305°
	30	8	353°									0	305°
	31	6	343°	2	037°							0	305°
Sept.	1	7	148°	3	170°							1	305°
	2	21	211°	2	198°							3	125°
	3	24	199°	2	002°							0	125°
	4	12	160°	1	022°							0	305°
	5	11	167°	0	270°							0	305°
	6	6	231°	3	354°	0	290°						
	7	3	068°	1	013°	0	290°						
	8	3	125°	5	132°	0	--						
	9	11	189°	1	321°	5	110°						
	10	10	205°	2	058°	4	290°						
	11	11	117°	6	133°	1	290°						
	12	21	198°	3	079°	5	110°						
	13	12	175°			1	110°						
	14	12	202°			2	110°						
	15	3	151°			1	290°	4	140°				
	16	11	208°			2	290°	1	140°				
	17	6	240°			3	290°	2	320°				
	18	2	027°			4	290°	1	140°				
	19	10	033°			3	290°	1	320°				
	20	13	076°			3	290°	0	140°				
	21					3	290°	2	140°				
		MEAN		MEAN		MEAN		MEAN		MEAN		MEAN	
		6.0	185°	1.1	101°	0.2	290°	1.2	140°	2.6	075°	0.1	125°

r = rate in miles for day, d = direction towards which current sets probable error. The residual current in this area can be summarized as generally weak and variable in direction. The one exception being the current recorded at H_1 during the period August 9 - 11, when it set consistently at fairly strong rates in a southeasterly direction.

In the western part of the Strait, sites K_5 and K_{10} are situated in mid-channel westwards and southwestwards, respectively, from West Point, while L_1 lies about 5 miles westward from North Point. At the first two sites, the residual current is generally southeastwards setting weakly into the Strait. The strongest sets in this direction at K_5 occur during the period August 9 - 15. At L_1 the set, whenever greater than 2 miles per day, was in an easterly direction, and probably forms part of the easterly set along the north coast of the Island.

The remaining site, F_1, is south of Hillsborough Bay, and it was there that the greatest mean residual rate was observed; this sets southeastwards in the general direction of George Bay. It might be thought that this outset from Hillsborough Bay was mainly due to the rivers flowing into it. However, there was no evidence of a strong outflow in the Bay itself from a single day's observations obtained at F_2. The large mean residual rate at F_1 is mainly accounted for by the very strong sets experienced during the period August 9 - 15. It has already been noted that during part, or the whole, of this period unusually strong southeasterly sets were experienced at H_1 and K_{10}, and it would appear that these conditions were somewhat exceptional.

Thus, the general pattern suggested by these automatic meter observations is of generally weak residual currents in the central part of the Strait, with occasionally fairly strong sets to the southeastward. In the eastern entrance, off East Point, there is usually a strong inset, while in the western entrance, off

North Point, there is generally an outset. There is thus a contradiction between the sets experienced in the two entrances and those experienced in the central part of the Strait. It may, however, be possible to show that the inset in the eastern entrance is confined to the vicinity of East Point and that the outset in the western entrance is confined to the vicinity of North Point.

Direct Observations from the Ship

The residual currents determined by observations for periods of 24 hours, from the ship at anchor, are subject to the day-to-day fluctuations already referred to. These observations were only taken at 30-minute intervals and are therefore less reliable than the continuous recordings by the automatic current meters. The latter have also the advantage that the automatic meter floats submerged at a depth of about 30 feet and, in consequence, the direction and distances recorded do not include the errors caused by wind-induced movements of the point of observation , as is the case with the ship. However, it was considered that the means of the residuals, found at a number of ship sites in the same vicinity, should be of some value in broadening the pattern of residual flow indicated by the automatic current meter observations. The means from groups of ship sites and those from individual automatic meters are given in Table 5b, page 72.

In the eastern entrance, the residuals determined in the A, AB and B sections were very erratic and showed no consistency between adjoining sites or between different depths at the same site. The vector means of those residuals, as given in Table 5b, have only a negative value, in that they indicate that the strong inset off East Point does not persist right across the Strait.

TABLE 5b

SUMMARY OF RESIDUAL CURRENTS

SITES	r	d	SITES	r	d	SITES	r	d
EASTERN ENTRANCE								
West Side			Middle			East Side		
A_1	5.5	129°	A_2, A_3)			A_4)		
AB_1	6.0	185°	AB_2, AB_3,)	1.1	255°	AB_4,)	*2.7	292°
B_1	3.8	024°	B_2, B_3)			B_4)		
BELL POINT - CAPE GEORGE								
North Side			Middle			South Side		
C_1)			C_2, C_6, C_7)			C_3, C_5)		
D_1)	1.6	134°	D_2)	0.8	172°	D_3)	1.2	183°
E_1)			E_2)			E_3)		
BAIE VERTE - POINT PRIM								
North Side			Middle			South Side		
F_1	9.6	136°	F_3)			F_4)		
G_1	1.1	101°	FG_1, FG_2)	1.5	111°	FG_3)	0.6	102°
			G_2)			G_3, G_4, G_5)		
CAPE EGMONT - CAPE TORMENTINE								
North Side			Middle			South Side		
H_3, H_4, H_5)			H_6	0.3	264°	H_1	0.9	236°
I_1)	0.9	054°	I_2	0.7	290°	H_7, H_8, H_2)		
J_1)			J_2	0.1	125°	I_3, J_3)	2.2	126°
WESTERN ENTRANCE								
East Side			Middle			West Side		
L_2)	*0.7	333°	L_3, K_2, K_8	*1.4	062°	K_9, K_4, K_3)		
K_7, K_6, K_1)			K_5	1.7	167°	L_4)	1.3	168°
L_1	*2.6	075°	K_{10}	1.7	140°			

r = rate in miles per day, d = direction towards which current sets

* Set out of Strait.

In the central parts of the Strait the residuals on the sections from C to J confirm the conclusion, reached from the automatic current meter observations, that there is a very weak set in a generally southeastward direction towards George Bay, whose entrance lies between Ballantynes Cove and Port Hood.

In the western entrance there is a fairly clear indication of an inset on the western side, in opposition to the outset found close to North Point.

General Pattern of Residual Flow

In the western entrance there is a weak southeasterly set into the Strait, part of which eddies out again near the shore of Prince Edward Island. This weak southeasterly set persists throughout the central part of the Strait and is directed towards George Bay. In the eastern entrance there is an inset on the western side, part of which eddies northwards further inshore, but which is mainly directed also towards George Bay.

Prior to the construction of the Canso causeway there was a fairly strong set through the Strait of Canso from George Bay towards the Atlantic Ocean. The residual currents, at two ship sites in the entrance to George Bay, set in a northeasterly direction, and it would appear that the former outset through the Strait of Canso has been replaced by a fairly strong northeasterly outset along the shore of Cape Breton Island.

Residual Currents as Determined by Oceanographical Observations

These observations, which were very much less comprehensive than the direct observations, were analysed by the Atlantic Oceanographical Group, Fisheries Research Board of Canada. Its report is included as Appendix D.

The salinity and temperature observations were obtained at stations occupied for 24 hours only, and not at those sites where the automatic current meters were moored. In consequence, the residual flow in the eastern entrance has been deduced from oceanographical observations taken only in the middle and eastern parts of the Strait. The period during which these oceanographical observations were taken - September 18 - 20 - happened to be one during which the residual current at AB_1 was setting fairly strongly out of the Strait, contrary to its usual practice. In consequence the oceanographical deductions of an outflow in the upper layers may be based on conditions which were somewhat exceptional.

Conclusion

Under settled weather conditions the residual currents in the vicinity of the proposed causeway are weak and somewhat uncertain in direction. It seems improbable that they can have any appreciable permanent affect in transporting material in suspension, and it is equally unlikely that they account for movements of ice which are more probably due to the prevailing west to northwest winds in the winter months.

In the Gulf of St. Lawrence minor oscillations in sea level, generated by changes in meteorological conditions, are a frequent occurrence even in the summer months. There is a transport of water through Northumberland Strait, associated with these oscillations, which temporarily dominates the long-term residual flow. With the major meteorological disturbances, which generate storm surges, these temporary residual movements will be strong and could reach rates of 2 knots near the site of the causeway. These residuals will be alternately west and eastgoing for periods of 12 to 14 hours, which approximately coincide with the periods during which sea level is raised and lowered by the surge. The actual flow experienced at any time will be the resultant of the tidal streams and residual current.

6. SUMMARY OF CONCLUSIONS

The division of Northumberland Strait into two separate gulfs, as the consequence of the construction of an unbroken causeway, would bring about marked periodic differences in the levels on its two sides, and would cause considerable increases in the range of the tide in the western part of the Strait, with lesser increases just eastward and westward of the causeway. These increases in range will result in a raising of the high-water levels and a lowering of the low-water levels. There will be some increase, near the site of the causeway, in the effects of weather conditions upon sea level at any state of tide.

Differences in Level at the Causeway

The periodic differences in level on the two sides of the causeway will develope with its construction, and give rise to an increasingly violent flow through the gap as closure approaches. When the causeway is complete the greatest difference in the tidal levels on either side will be about 10 feet. When the causeway is nearly complete, strong winds blowing down the Strait will create large differences in level on the two sides, independently of the periodic differences created by the tides. With a very adverse combination of tidal and meteorological conditions - a rare occurrence, the two effects might temporarily supplement one another, creating an exceptionally large head of water and hence an exceptionally violent flow of water through the gap. This risk will exist only for the relatively short period while the gap is very narrow.

Increase in Tidal Range

(see Tables 3a and 3b, Figure 3g, pages 34, 37, 38)

(a) In the area extending along the New Brunswick shore from eastwards of Cape Bald to the entrance to Buctouche River and across the Strait to Cape Egmont, there will be an increase of more than 3 feet under average, and of at least 5 feet under fairly extreme, astronomical conditions.

(b) In the area extending westwards from the causeway to the eastern limit of the area described in (a), there will be an increase of 1 1/2 to 3 feet under average, and 2 1/2 to 5 feet under fairly extreme, astronomical conditions.

(c) In the area extending eastwards from the causeway to a line joining Canoe Cove, and Cape Cliff, the increase will diminish from 3 1/2 to 2 1/2 feet under average, and from 4 1/2 to 3 1/2 feet under fairly extreme, astronomical conditions.

(d) In the area extending eastwards from the eastern limit of the area described in (c) to a line joining Murray Harbour and Pictou, the increase will diminish from 2 1/2 to 3/4 feet under average, and from 3 1/2 to 3/4 feet under fairly extreme, astronomical conditions.

<u>Rises in High Water Levels</u>

(see Figure 3h, page 39)

In area (a), under fairly extreme astronomical conditions, the high-water levels will be raised by 3 to 3 1/2 feet. It is not considered that the present effects of weather conditions in raising sea level will be appreciably increased.

In area (b) the high water levels will not be raised by the changes in the tide to the same extent as in area (a), but in view of a probable increase in the effects of weather conditions near the site of the causeway the resultant will be about 3 1/2 feet.

In area (c), under fairly extreme astronomical conditions, the high-water levels will be raised by the changes in the tide by amounts which diminish from 2 to 1 1/2 feet. In view of a probable increase in the effects of weather conditions near the site of the causeway, the resultant will be about 3 1/2 feet at the causeway, diminishing to between 1 1/2 and 2 feet on the eastern border of this area.

In area (d), under fairly extreme astronomical conditions, the high-water levels will be raised by amounts which diminish from 1 1/2 feet near its western boundary to half a foot at the eastern boundary.

Falls in Low-water Levels

(see Figure 3i, page 41)

In areas (a) and (c) the low-water levels will fall by 1 1/2 to 2 feet under fairly extreme astronomical conditions. In areas (b) and (d) the equivalent amounts will be 1 1/2 to 1/2 feet.

Residual Currents

A regular flow throughout the Strait is hardly perceptible because these residual movements fluctuate very considerably with changes in meteorological conditions. The strongest residual currents, with rates up to 2 knots, probably occur with large surges travelling into and through the Strait, a west-going movement being associated with a rise in sea level and vice versa.

General

The forecast changes in tidal conditions can be accepted as reliable. The effects of the non-periodic fluctuations in meteorological conditions are much more complex and, in the absence of long-term data, forecast changes must be regarded as speculative.

APPENDIX A

TIDES AND TIDAL STREAMS NEAR PROPOSED SITE OF CAUSEWAY

In this area the characteristics of the tide and of the tidal stream differ, in that there is a relatively large diurnal component in the former and only a fairly insignificant one in the latter. In consequence there is no constant relationship between the occurrences of slack, or turn, of the tidal streams; the intervals between the two sets of occurrences will vary with astronomical conditions.

In order to refer the occurrences of slackwater to those of high water, it is necessary to select, as a Reference Port, a place where the diurnal component of the tide is equally insignificant. The most suitable port, for which daily predictions of the times of high and low water are given in the Atlantic Coast Tide and Current Tables, is Yarmouth, Nova Scotia.

In the middle and northern parts of the Strait between Cape Tormentine and Borden, the streams commence to flow eastwards about 55 minutes before low water at Yarmouth, and westwards about 35 minutes before high water at Yarmouth. In the shallow water near the Tormentine shore, in charted depths of about 5 fathoms, the streams turn about one hour earlier than in mid-channel and even closer to the shore may turn still earlier. To the west, in the whole area between Richibucto Head and Cape Egmont, the streams turn at about 30 minutes before the times of high and low water at Yarmouth.

The horizontal flow is the resultant of tidal stream and residual current. The residual currents vary considerably with astronomical conditions (<u>see</u> 5 RESIDUAL CURRENTS) and have quite appreciable effects upon the times at which slack water of the resultant occur.

In order to illustrate the flow through this part of the Strait and the differences in the elevation of the water under fairly extreme tidal conditions, the hourly rates and directions of the streams and the hourly heights of the tide were calculated for the astronomical conditions on November 13, 1958. They are shown on the hourly charts of Figures A_0 to A_{24}, pages 81 to 105 inclusive.

It will be seen that the tidal streams have their greatest rates - just over 2 knots - in the more restricted parts of the Strait, that is between Cape Tormentine and Borden, between Cape Bald and Cape Egmont, and, further to the westward, between Richibucto Head and West Point.

The semidiurnal amphidromic point lies between West Point and Buctouche, and the rise and fall of the tide increases with distance from the amphidromic point, the greatest range occurring just eastward of the narrows off Cape Tormentine. Thus, at high water the elevation near the latter is considerably higher than at Cape Egmont, while at low water the situation is reversed. On November 13, 1958, low water occurs at about 6 and 19 hours, and owing to the influence of the diurnal component the elevations are much lower at the first of these occurrences. The phase lag and amplitude of the diurnal component is uniform throughout this area and, consequently, raises or lowers the levels at all points by the same amount. Thus although the actual levels at Cape Tormentine and Cape Egmont are very dissimilar at the two occurrences of low water, on each occasion the level at Cape Tormentine is 2 feet below that at Cape Egmont. At high water the situation is reversed, for the level at Cape Tormentine is the higher and at each occurrence of high water the level there is 2 feet above that at Cape Egmont.

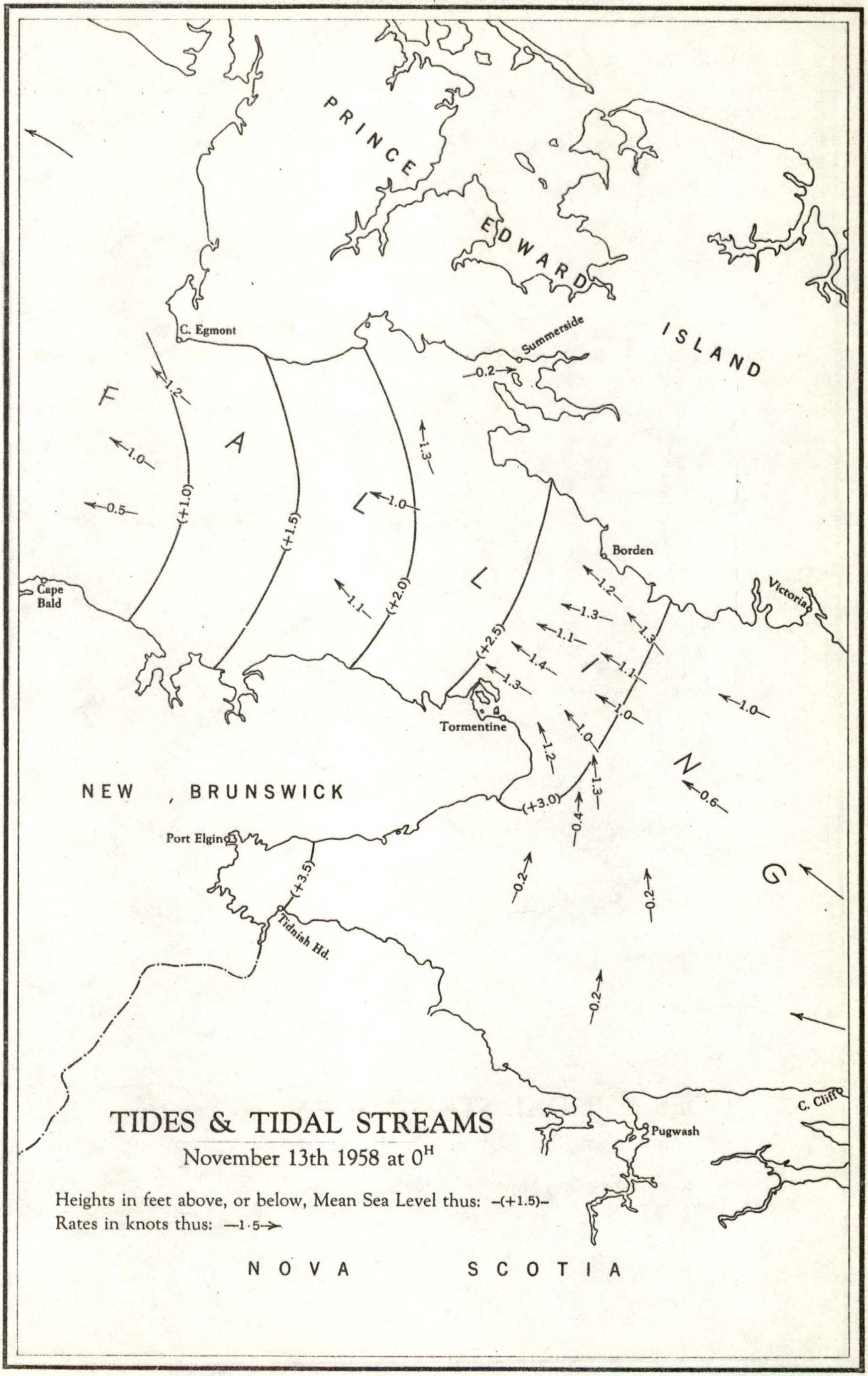
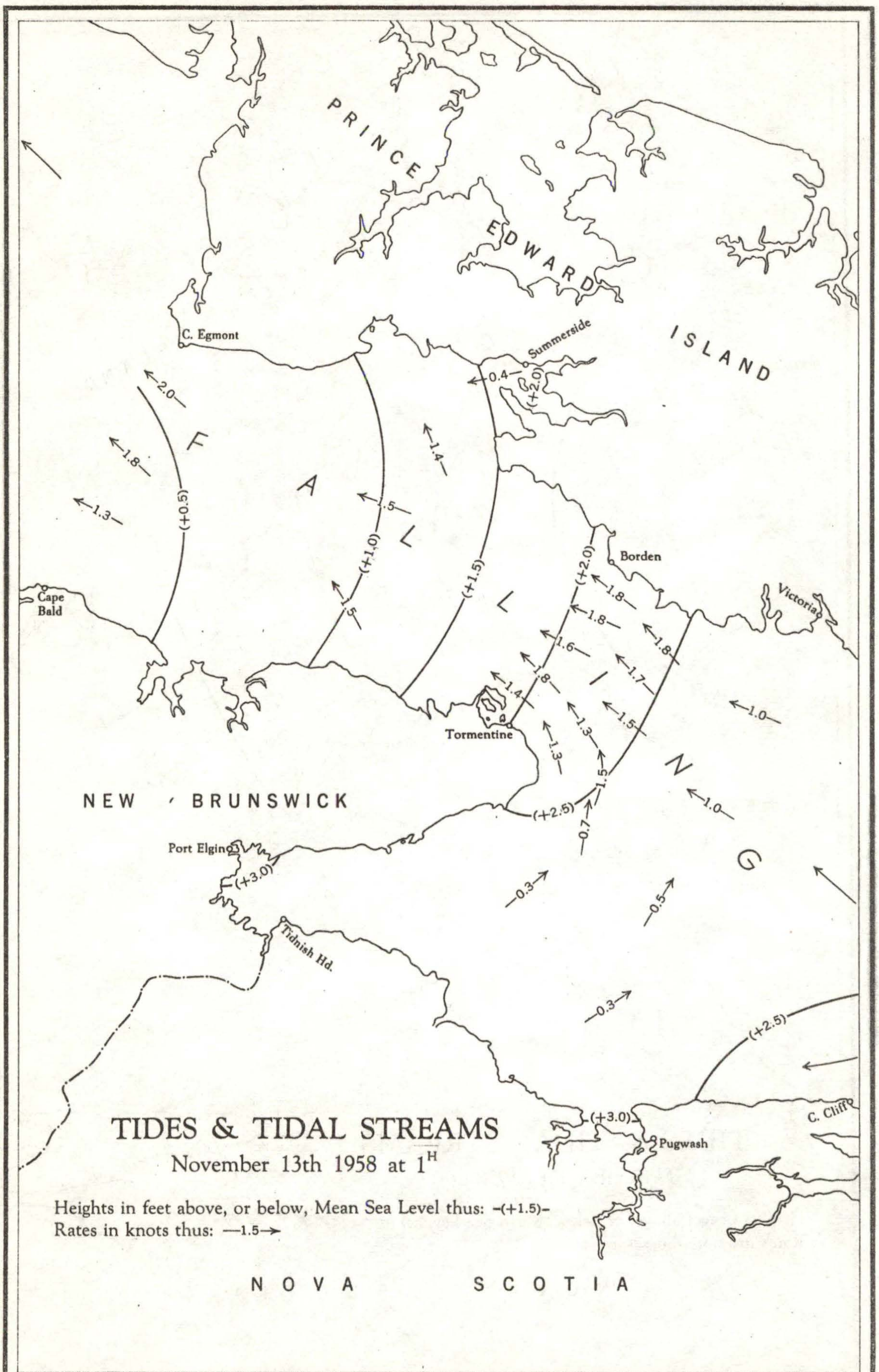

TIDES & TIDAL STREAMS
November 13th 1958 at 0^H
Heights in feet above, or below, Mean Sea Level thus: –(+1.5)–
Rates in knots thus: —1·5→
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
FALLING
C. Egmont
Summerside
Cape Bald
Borden
Victoria
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
(+1.0)
(+1.5)
(+2.0)
(+2.5)
(+3.0)
(+3.5)
1.2
1.0
0.5
1.3
1.1
0.2
1.4
0.6
0.4

Fig. A. 0



TIDES & TIDAL STREAMS
November 13th 1958 at 1^H

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.1

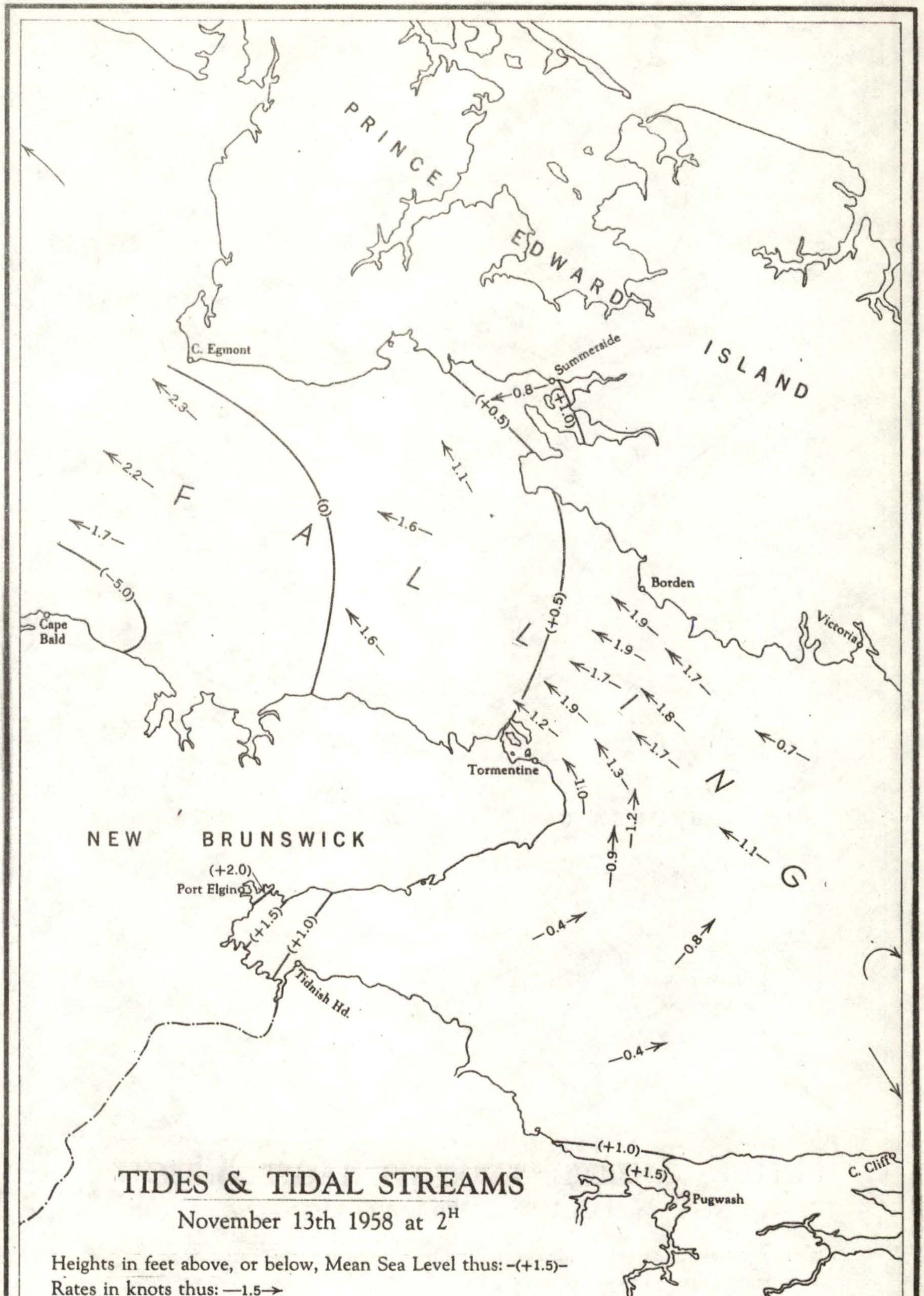

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
NEW BRUNSWICK
Port Elgin
Tidnish Hd.
C. Cliff
Pugwash
FALLING
NOVA SCOTIA
TIDES & TIDAL STREAMS
November 13th 1958 at 2H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A. 2

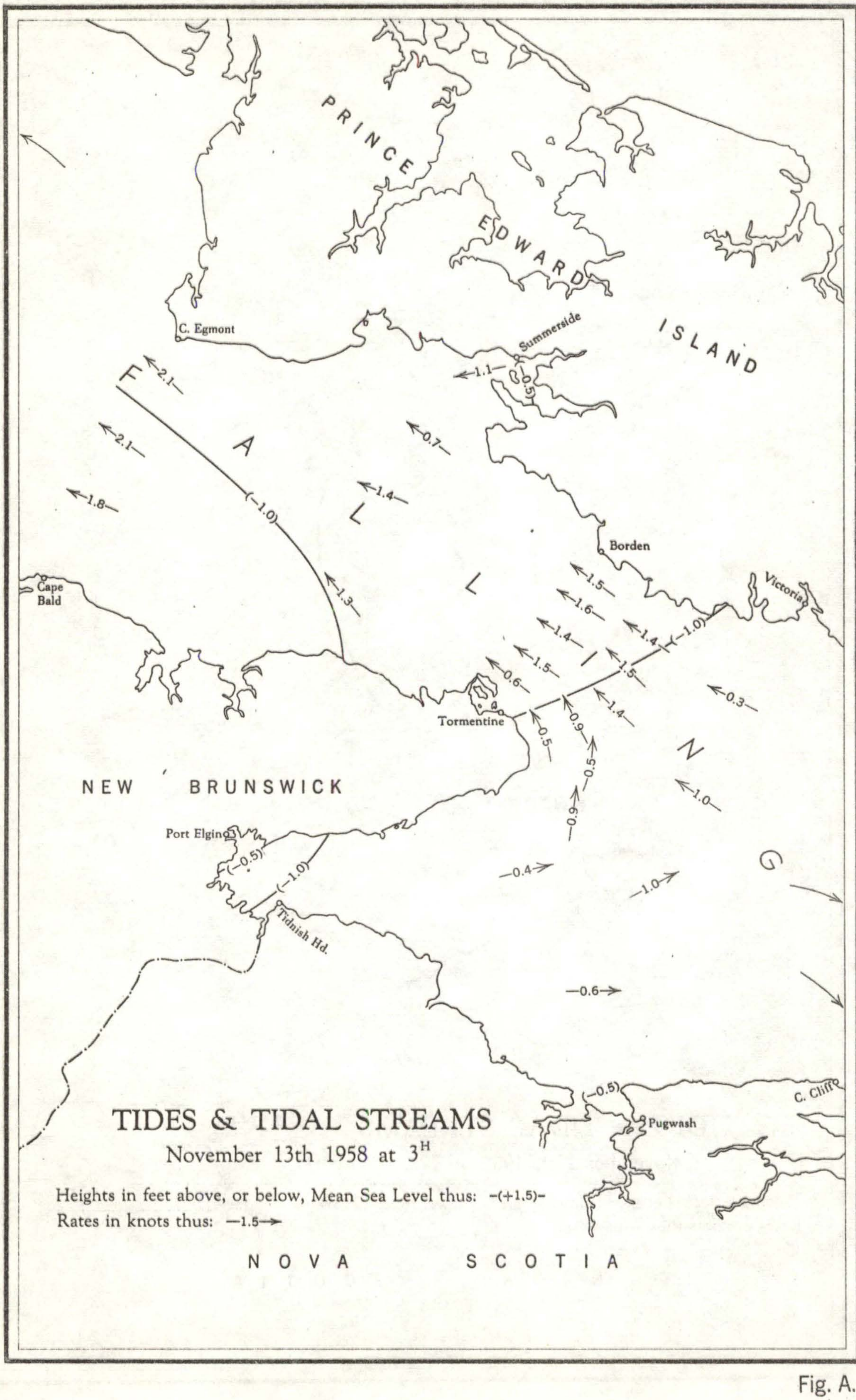

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
NEW BRUNSWICK
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
FALLING
NOVA SCOTIA
TIDES & TIDAL STREAMS
November 13th 1958 at 3H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.3

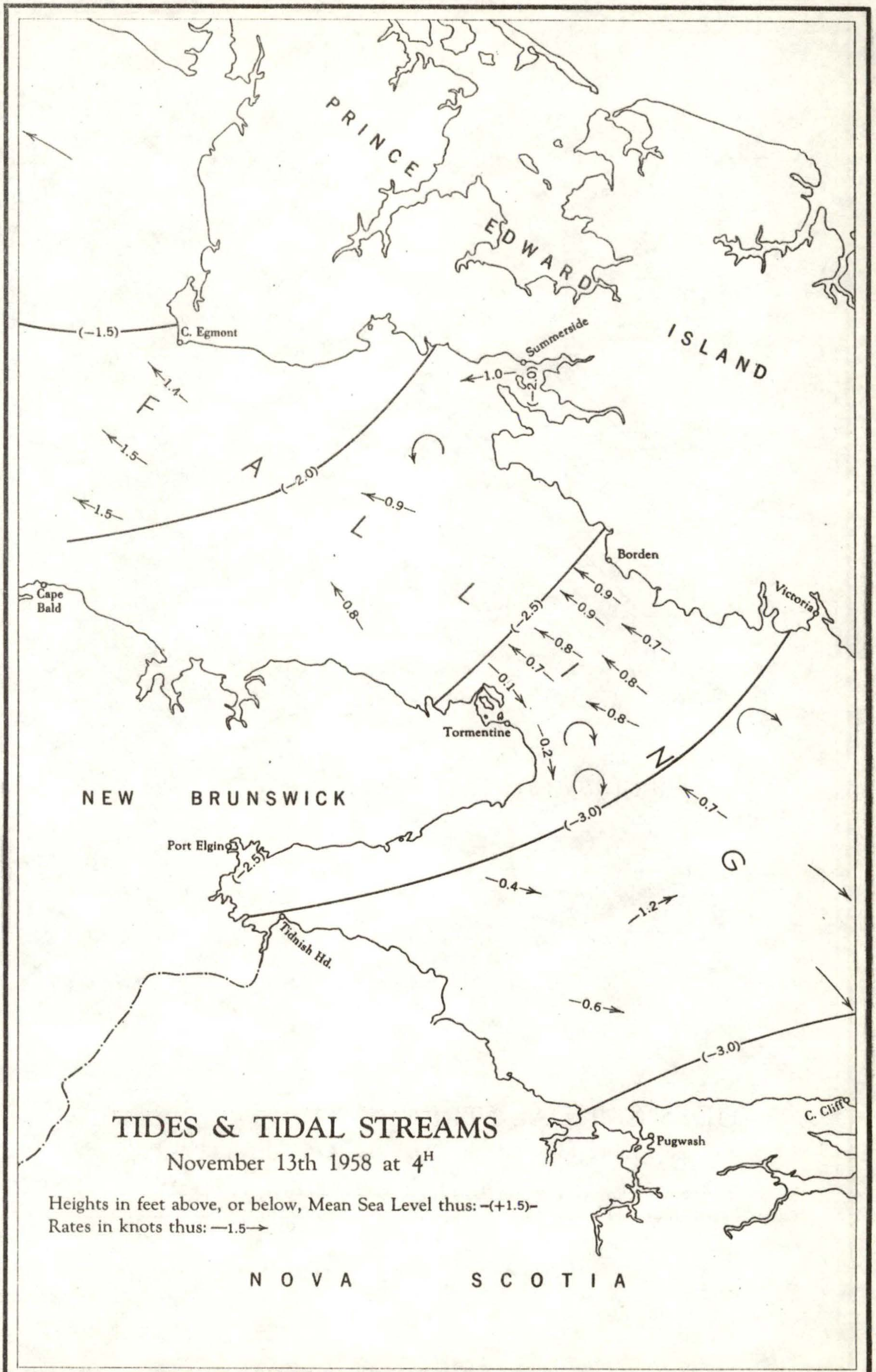
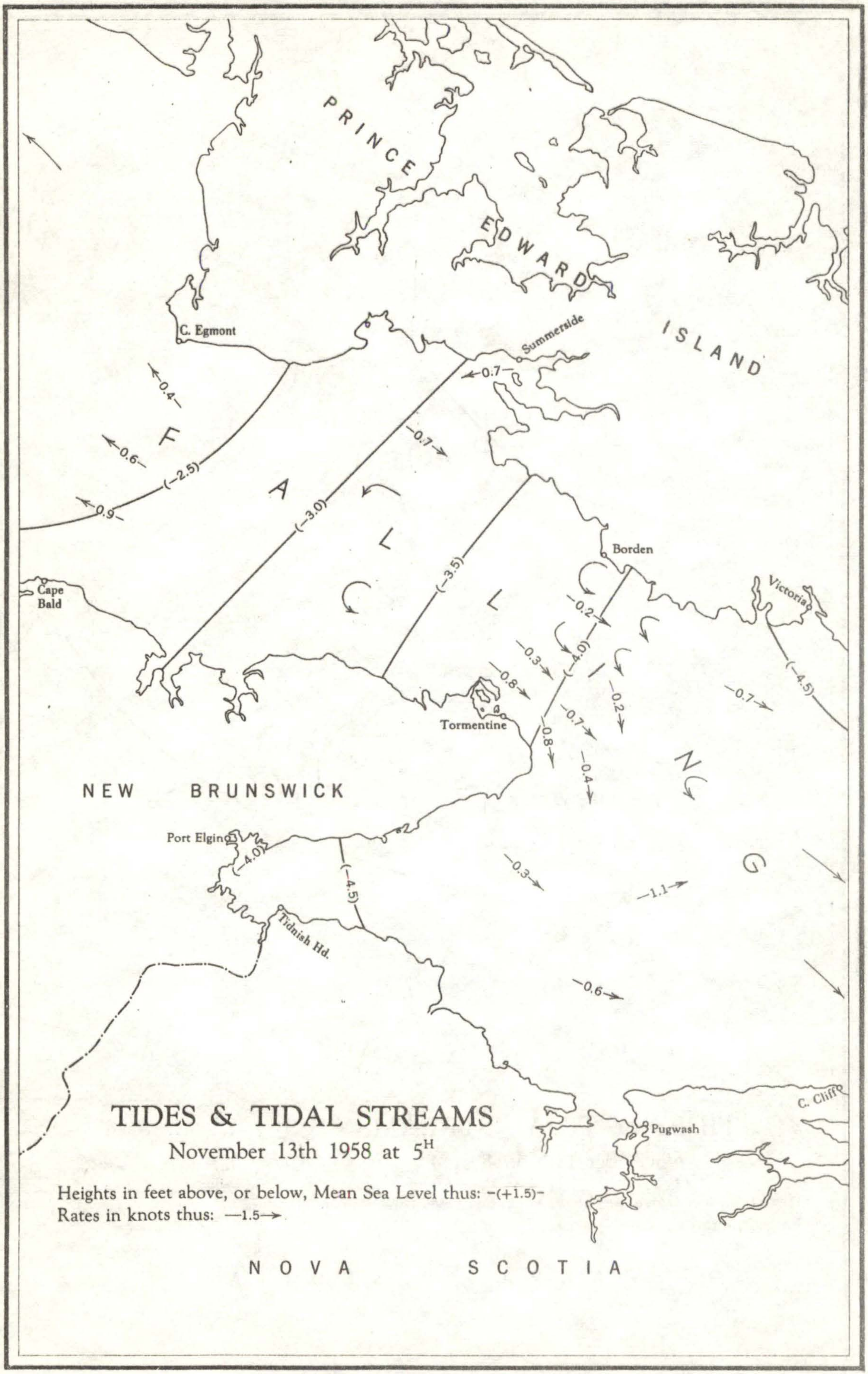

PRINCE EDWARD ISLAND
Summerside
C. Egmont
(−1.5)
FALLING
(−2.0)
1.1
1.5
1.5
1.0
(−2.0)
0.9
0.8
Borden
(−2.5)
0.9
0.9
0.8
0.7
0.7
0.8
0.8
0.1
0.2
Victoria
Cape Bald
Tormentine
NEW BRUNSWICK
Port Elgin
(−2.5)
(−3.0)
0.7
0.4
1.2
Tidnish Hd.
0.6
(−3.0)
C. Cliff
Pugwash
TIDES & TIDAL STREAMS
November 13th 1958 at 4^H
Heights in feet above, or below, Mean Sea Level thus: −(+1.5)−
Rates in knots thus: —1.5→
NOVA SCOTIA

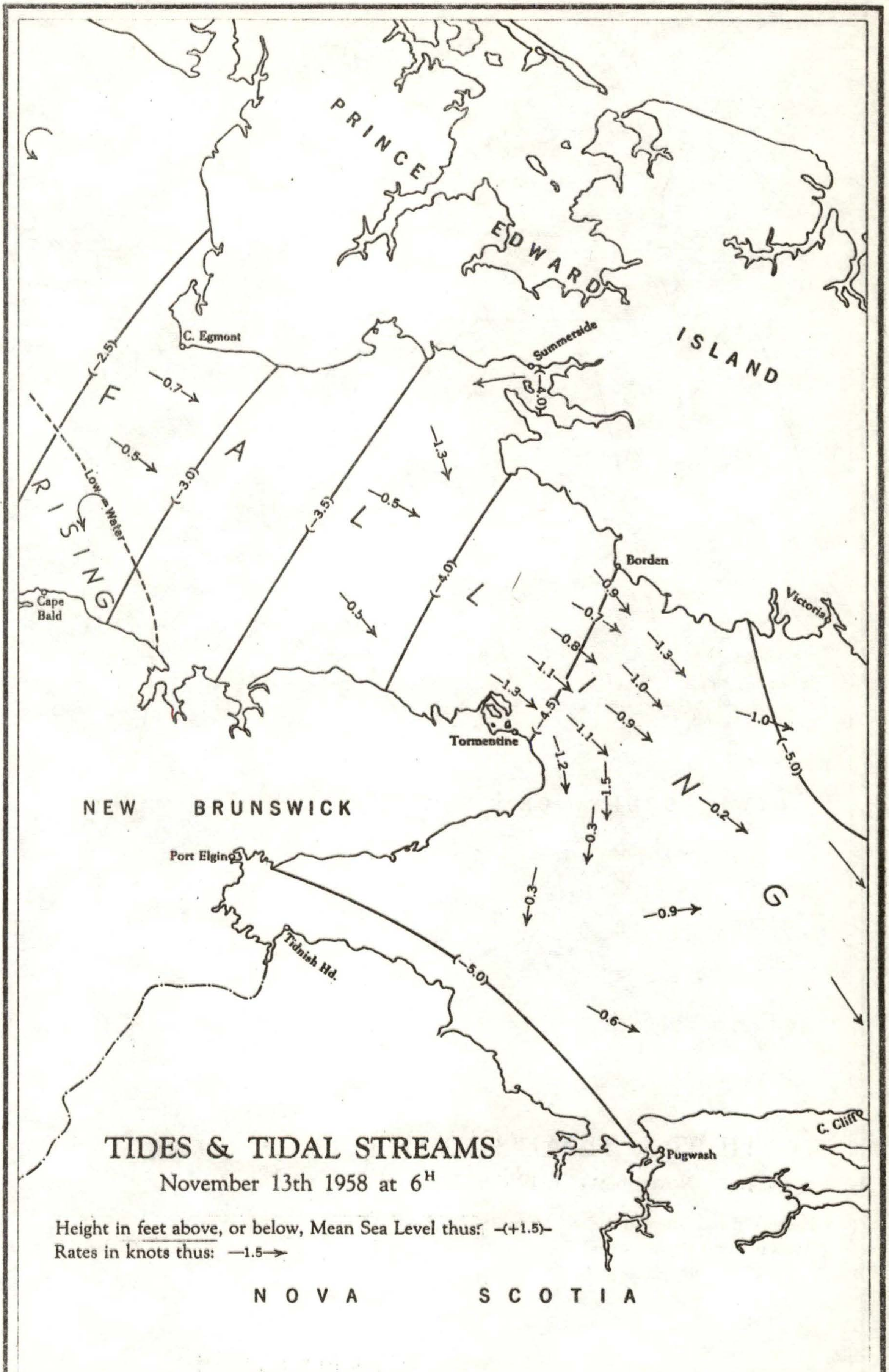
Fig. A. 4



TIDES & TIDAL STREAMS
November 13th 1958 at 5^H

Heights in feet above, or below, Mean Sea Level thus: –(+1.5)–
Rates in knots thus: —1.5→

Fig. A.$_5$



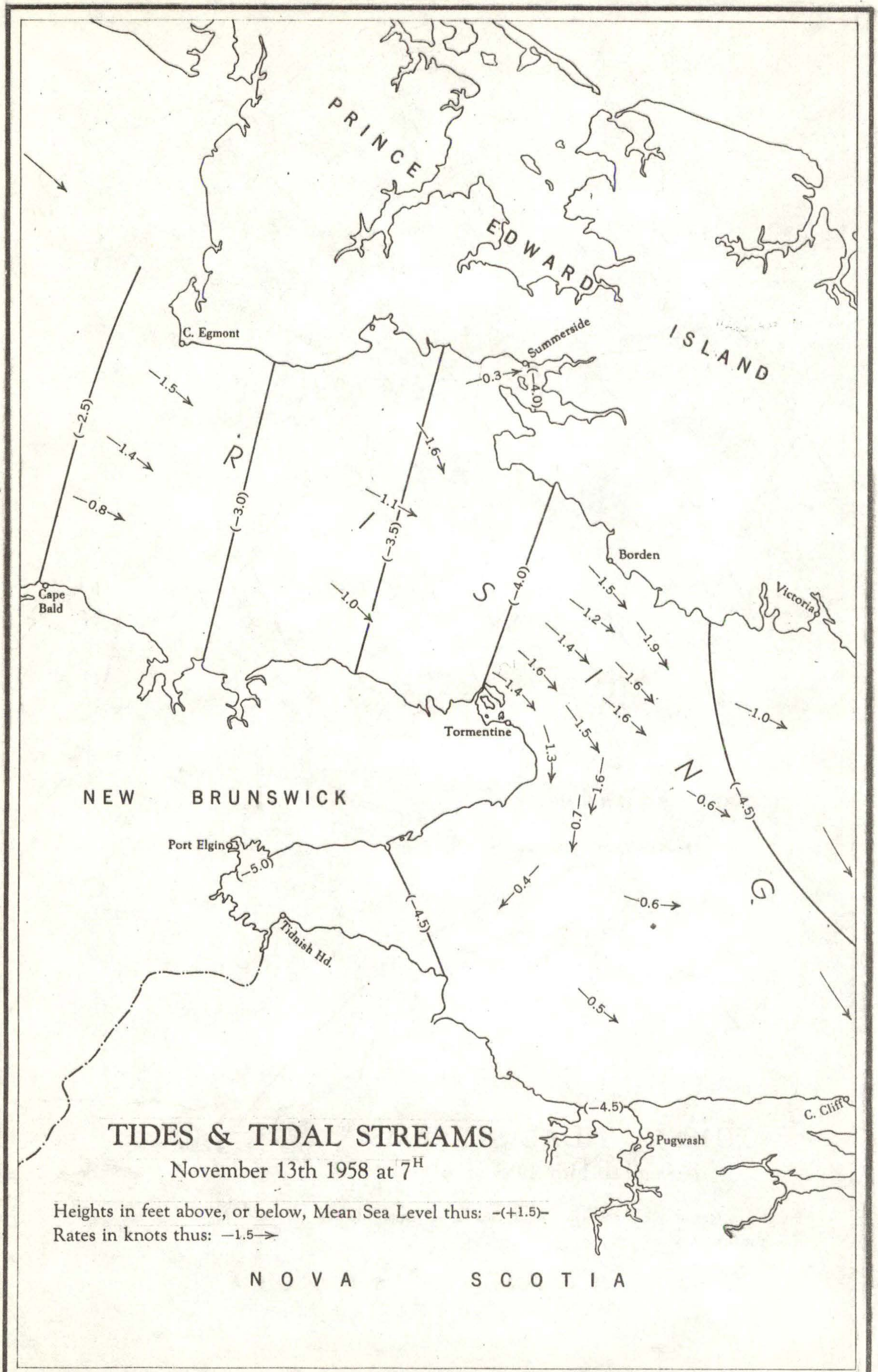
TIDES & TIDAL STREAMS

November 13th 1958 at 6^H

Height in feet above, or below, Mean Sea Level thus: -(+1.5)-

Rates in knots thus: —1.5→

Fig. A. 6



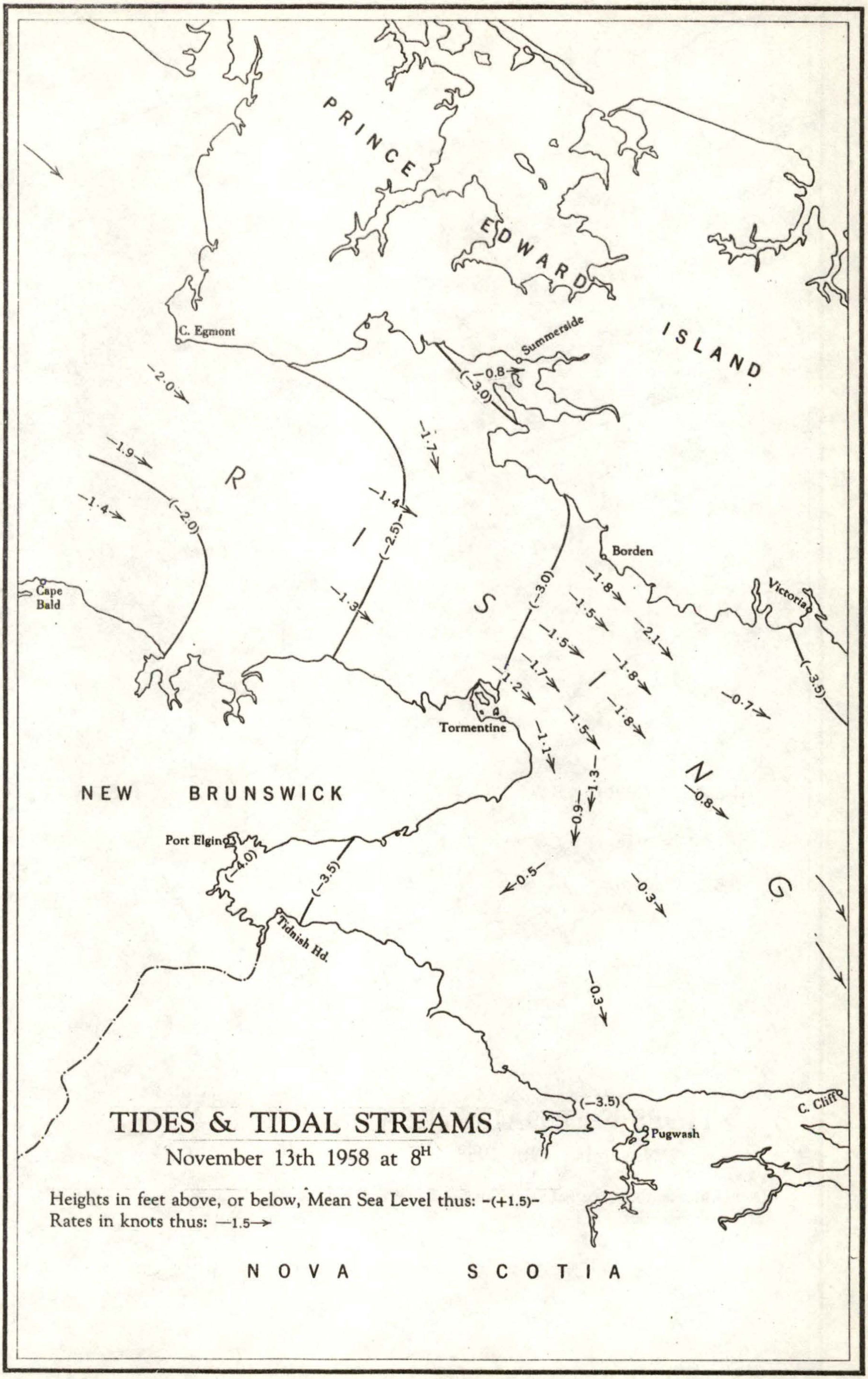
TIDES & TIDAL STREAMS

November 13th 1958 at 7[H]

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-

Rates in knots thus: —1.5→

Fig. A. 7



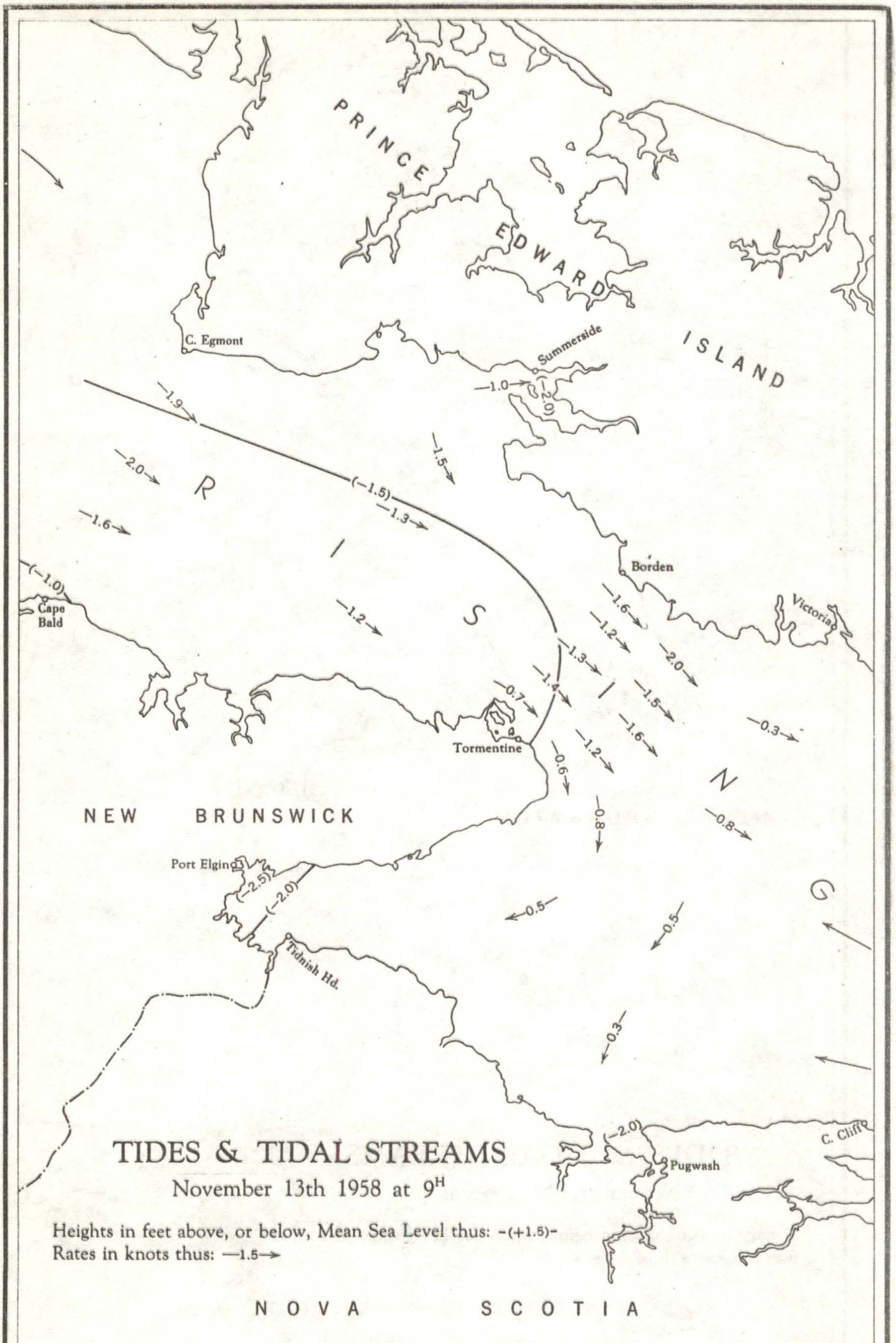
TIDES & TIDAL STREAMS

November 13th 1958 at 8^H

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-

Rates in knots thus: —1.5→

Fig. A. 8

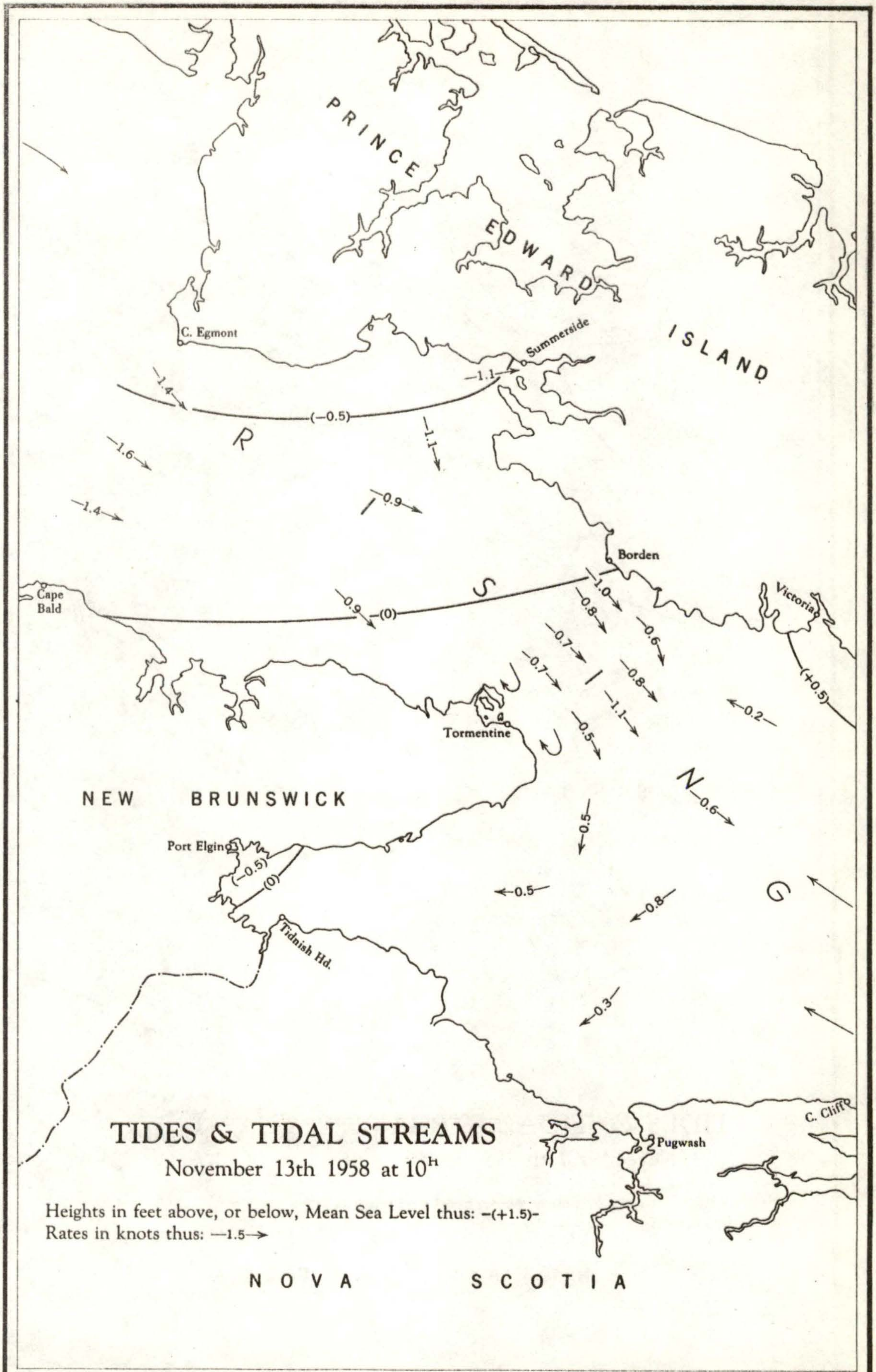


TIDES & TIDAL STREAMS

November 13th 1958 at 9^H

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A. 9

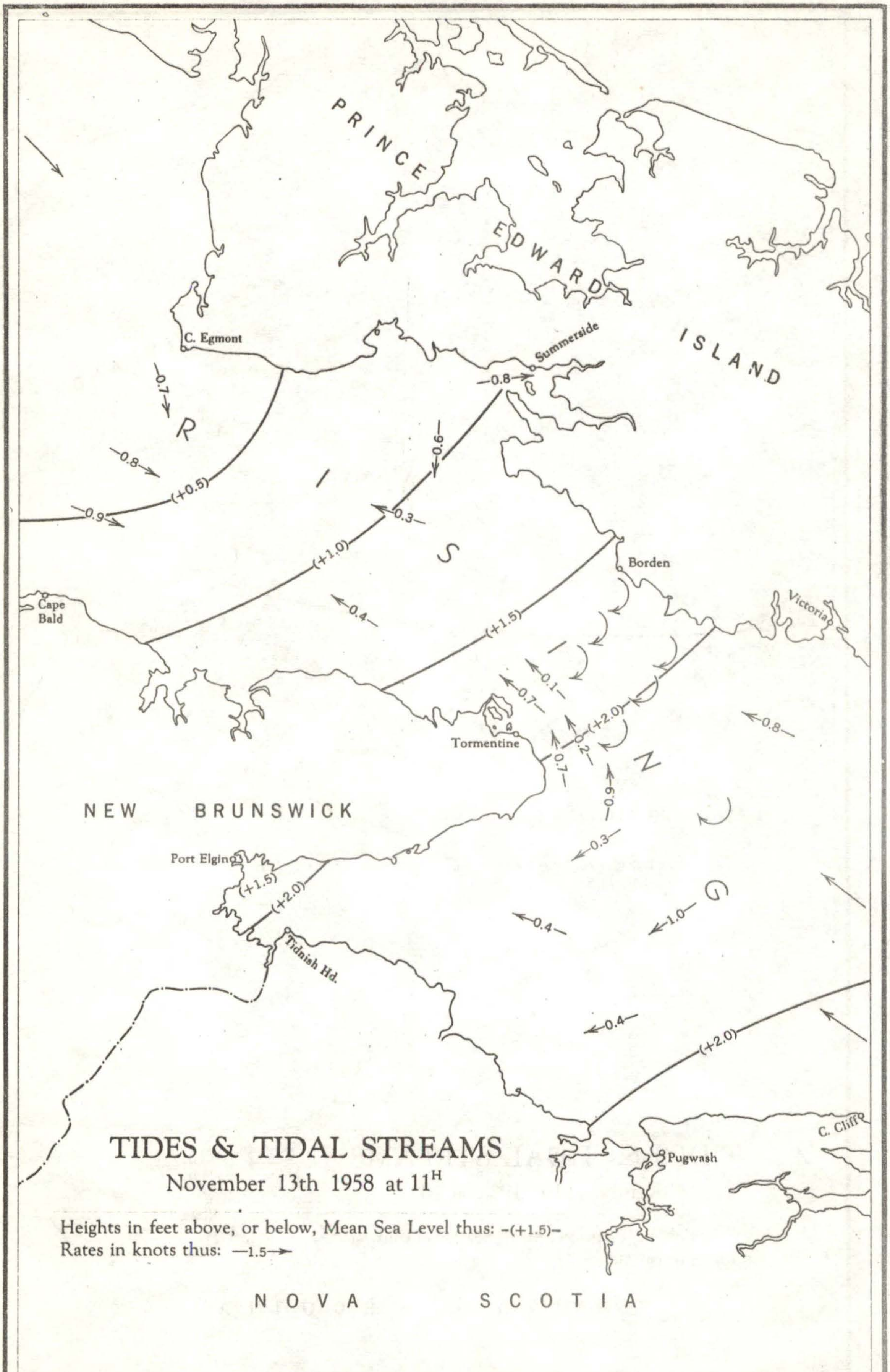


TIDES & TIDAL STREAMS

November 13th 1958 at 10^{h}

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A. $_{10}$

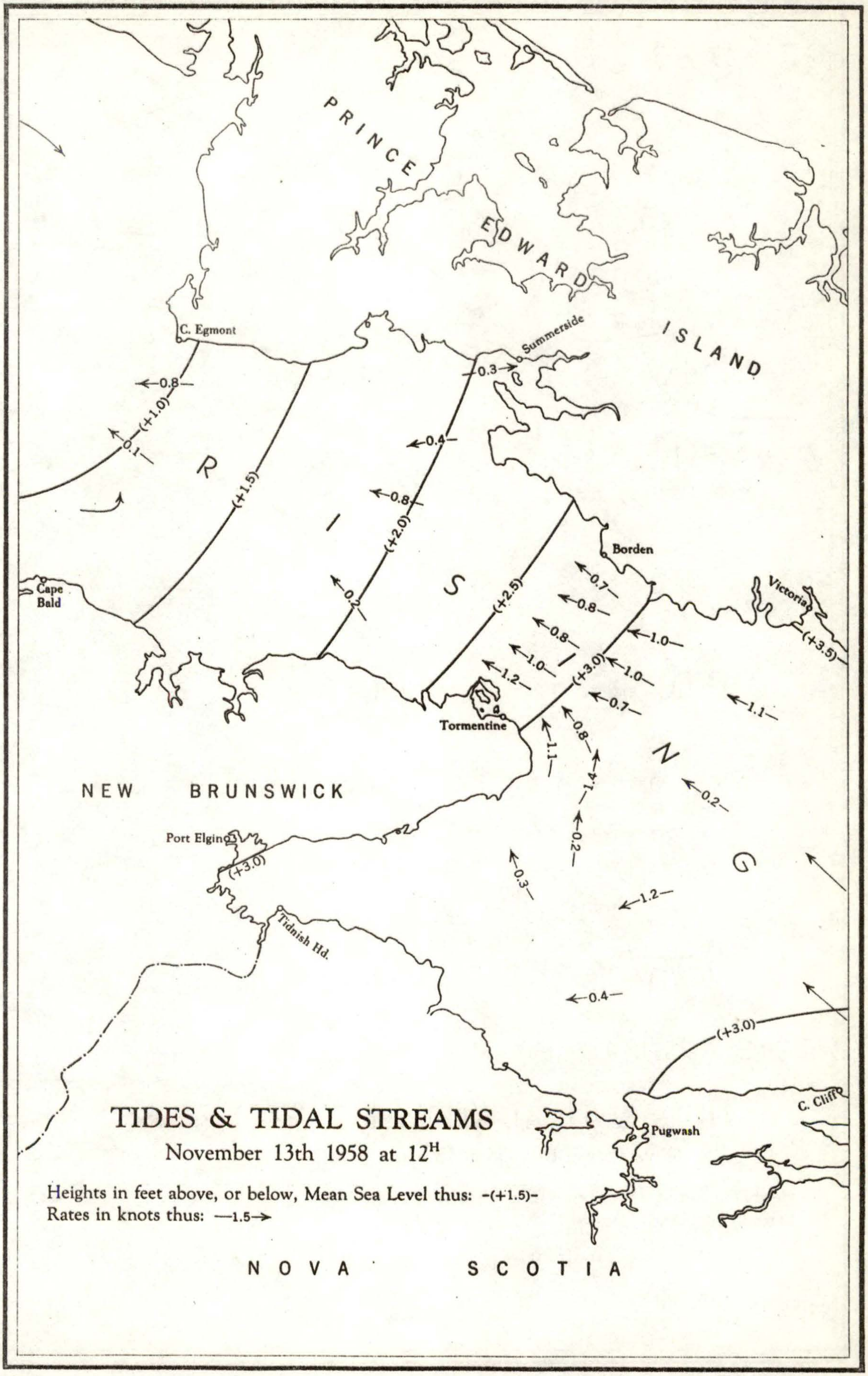


TIDES & TIDAL STREAMS

November 13th 1958 at 11^H

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.11



TIDES & TIDAL STREAMS

November 13th 1958 at 12^{H}

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.12

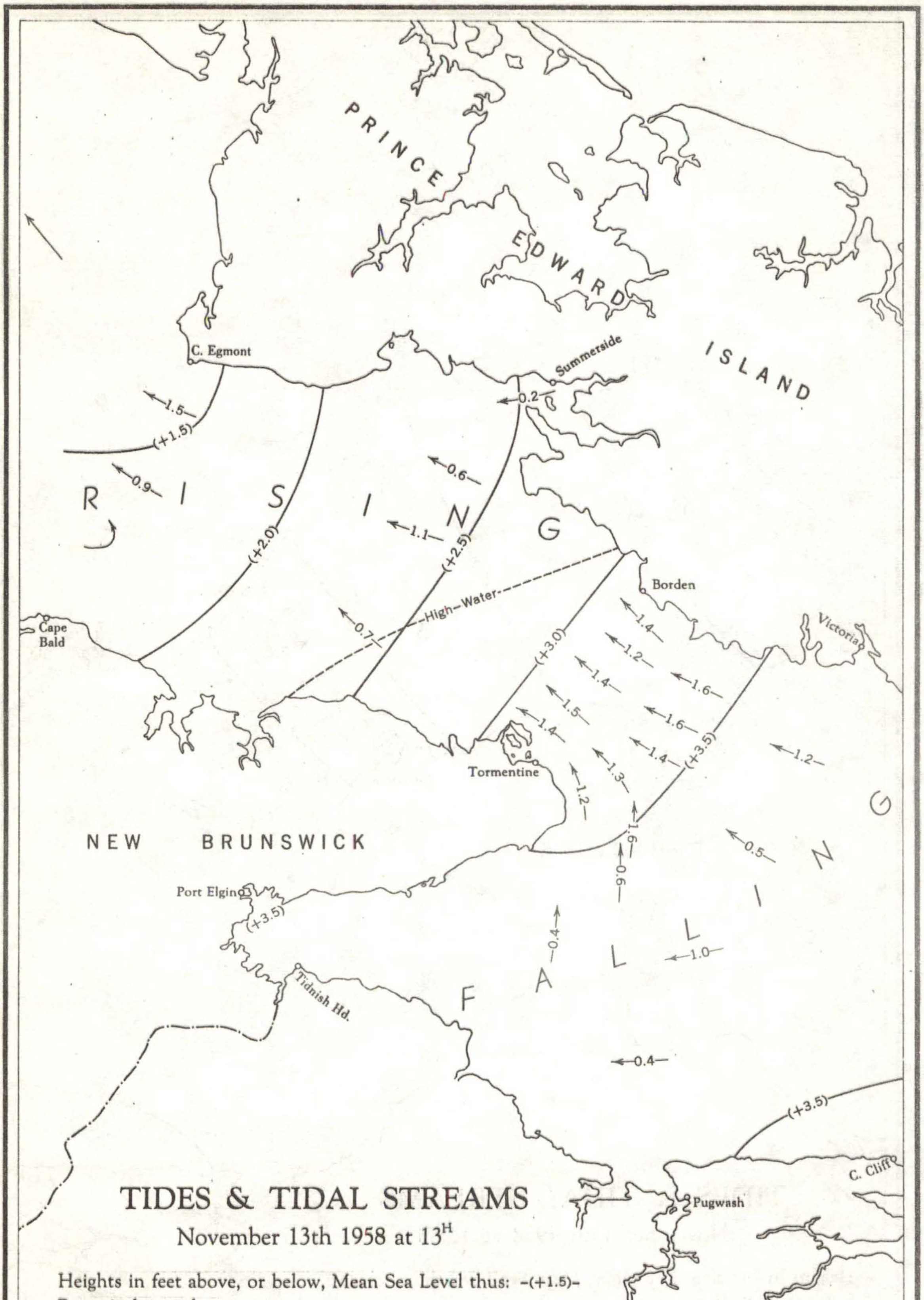

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Tormentine
Cape Bald
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
NEW BRUNSWICK
NOVA SCOTIA
RISING
FALLING
High-Water
(+1.5)
(+2.0)
(+2.5)
(+3.0)
(+3.5)
TIDES & TIDAL STREAMS
November 13th 1958 at 13H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.13

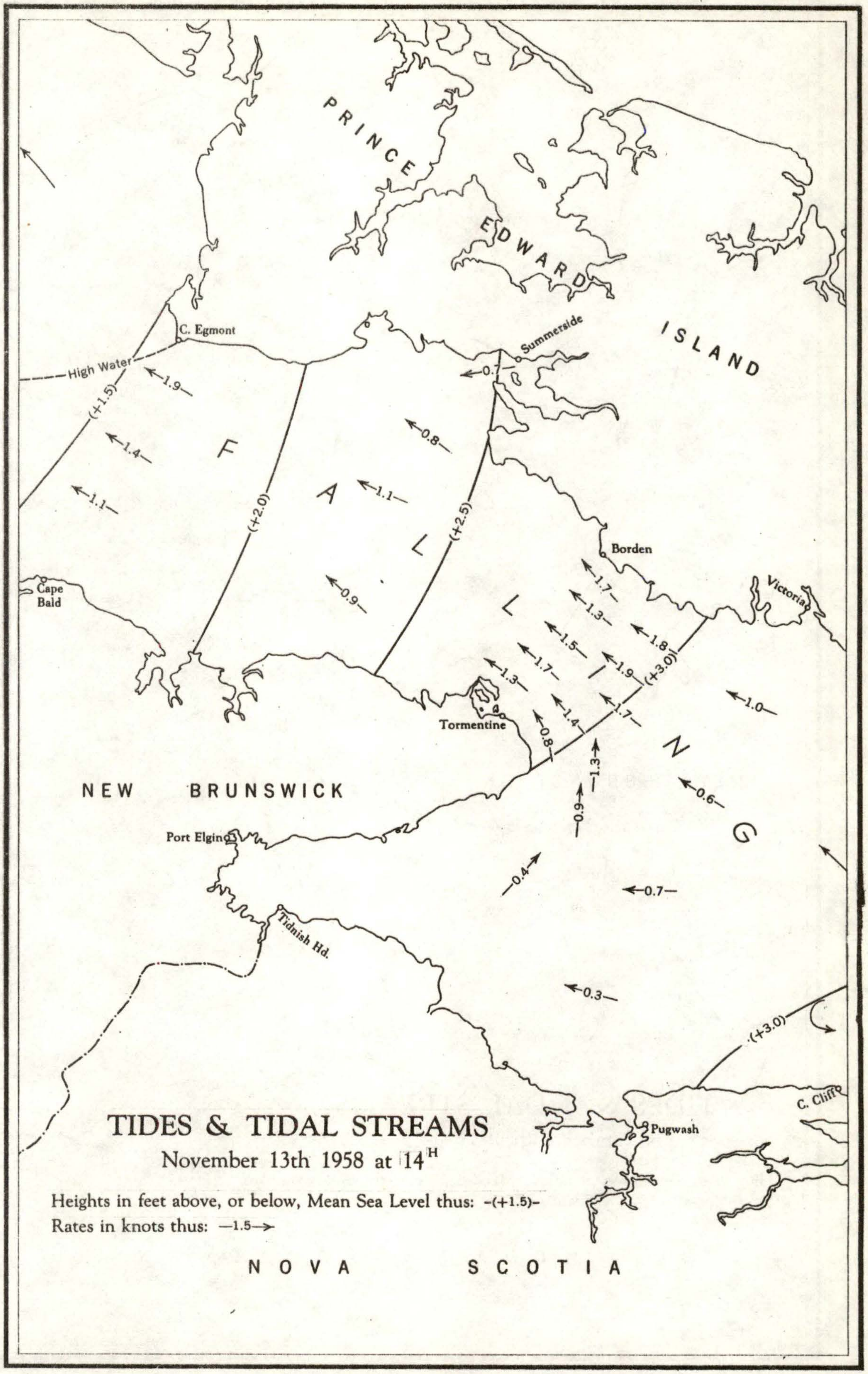

PRINCE EDWARD ISLAND
C. Egmont
High Water
Summerside
Borden
Victoria
Cape Bald
Tormentine
FALLING
NEW BRUNSWICK
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
NOVA SCOTIA
TIDES & TIDAL STREAMS
November 13th 1958 at 14^H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A. 14


PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
NEW BRUNSWICK
NOVA SCOTIA
FALLING
(+1.5)
(+2.0)
(+2.0)
(+2.0)
1.8
1.5
1.3
1.0
0.7
0.7
0.8
1.5
1.9
1.4
1.4
0.8
1.7
1.7
1.7
1.3
0.2
0.8
0.6
0.5
0.5
0.5
0.6
0.3
TIDES & TIDAL STREAMS
November 13th 1958 at 15H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.15

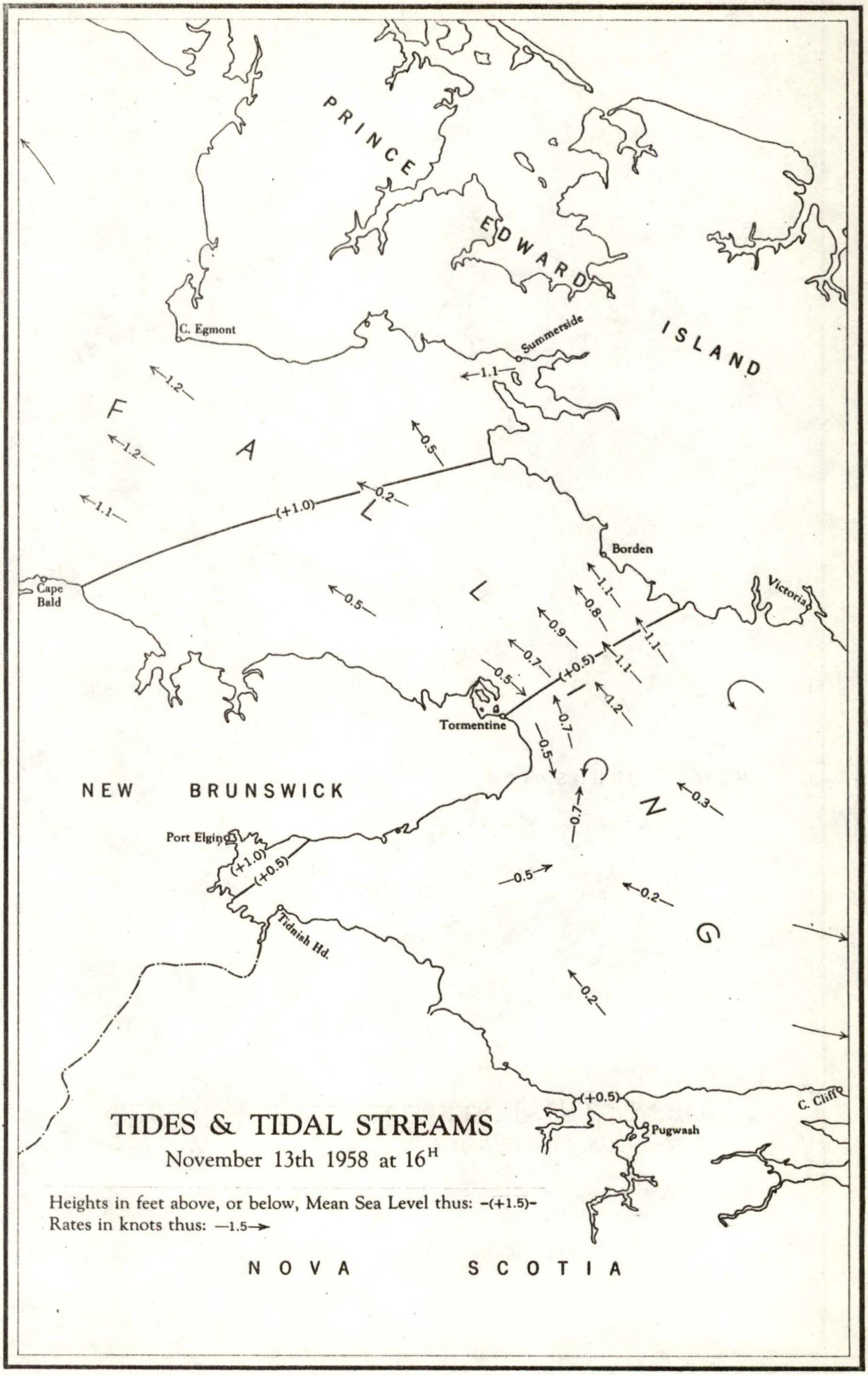

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
NEW BRUNSWICK
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
FALL
ING
NOVA SCOTIA
(+1.0)
(+0.5)
(+1.0)
(+0.5)
(+0.5)
TIDES & TIDAL STREAMS
November 13th 1958 at 16^H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.16

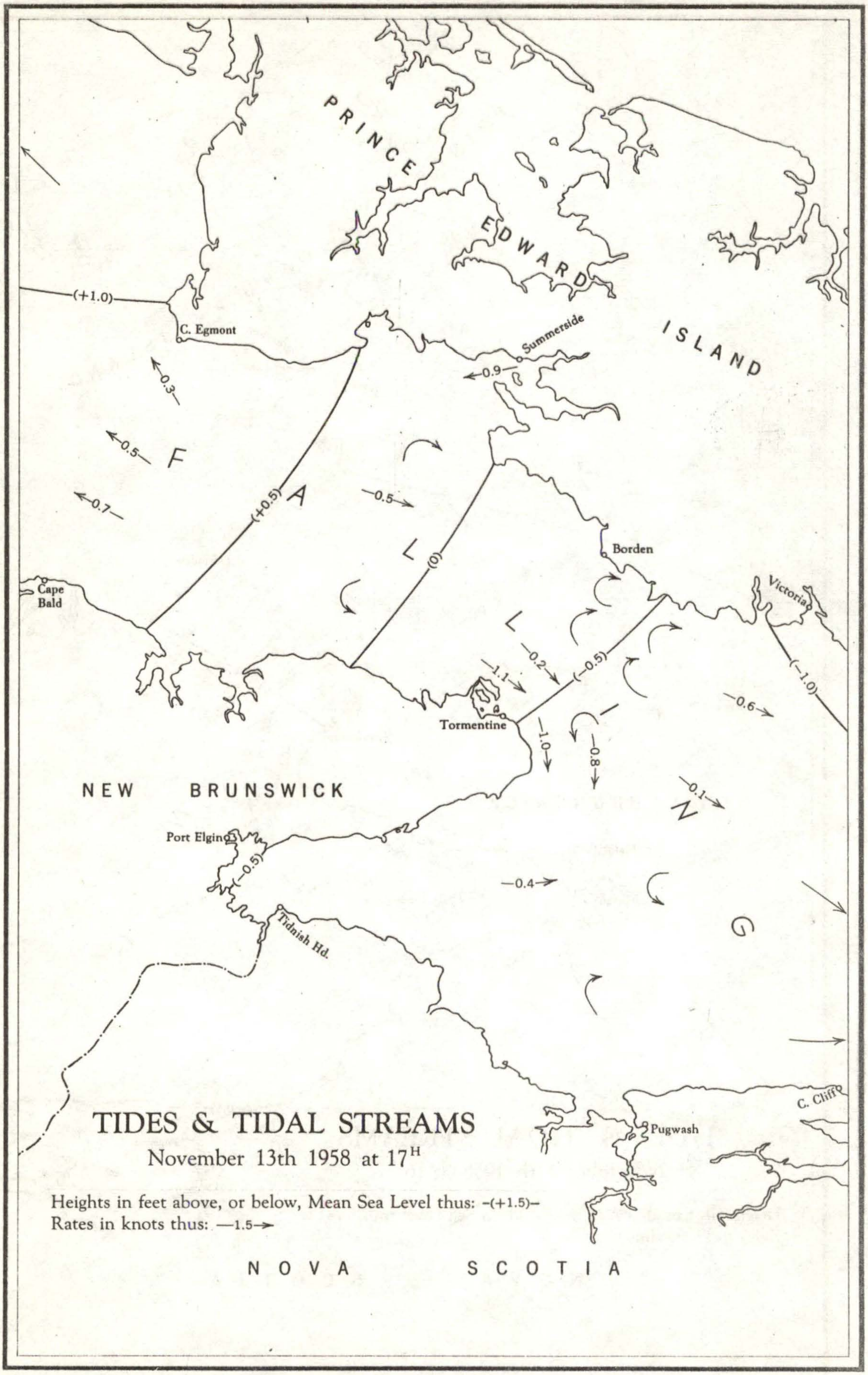
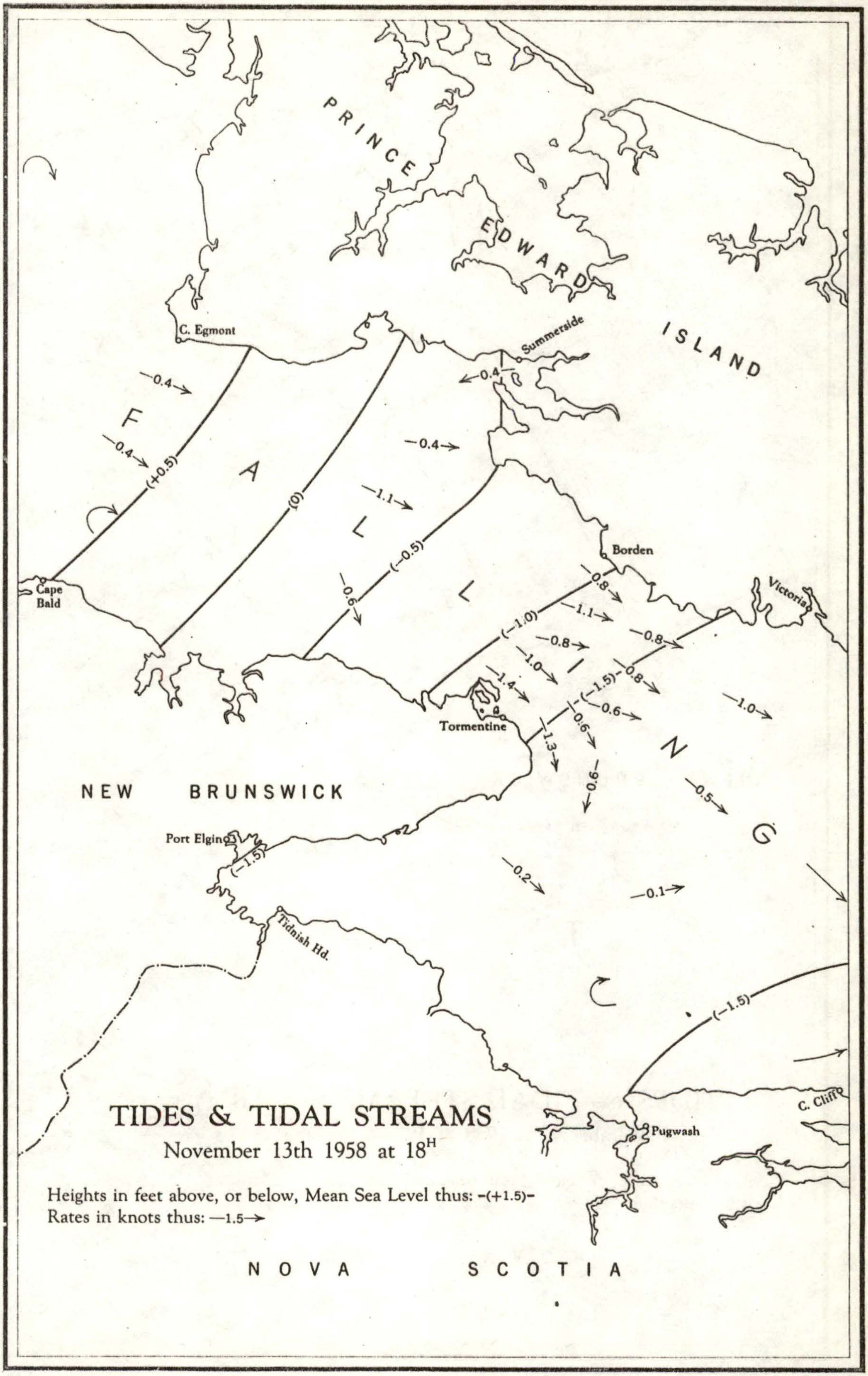

PRINCE EDWARD ISLAND
(+1.0)
C. Egmont
Summerside
0.9
0.3
0.5
0.7
FALLING
(+0.5)
0.5
(0)
Borden
Cape Bald
Victoria
0.2
1.1
(−0.5)
(−1.0)
0.6
Tormentine
1.0
0.8
0.1
NEW BRUNSWICK
Port Elgin
(−0.5)
0.4
Tidnish Hd.
C. Cliff
Pugwash
TIDES & TIDAL STREAMS
November 13th 1958 at 17H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→
NOVA SCOTIA

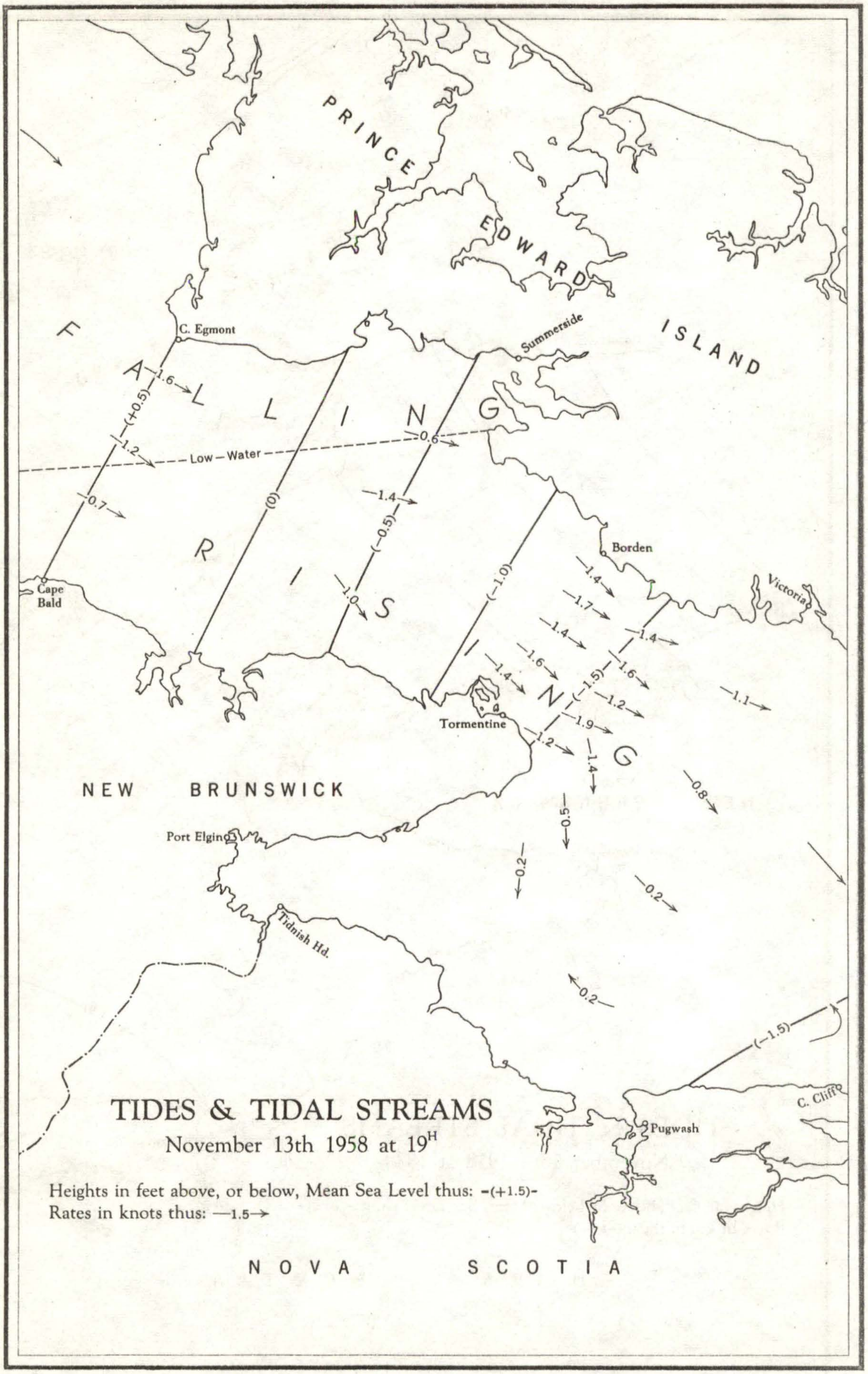
Fig. A. 17



TIDES & TIDAL STREAMS
November 13th 1958 at 18ᴴ

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A. 18



TIDES & TIDAL STREAMS

November 13th 1958 at 19^H

Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.19

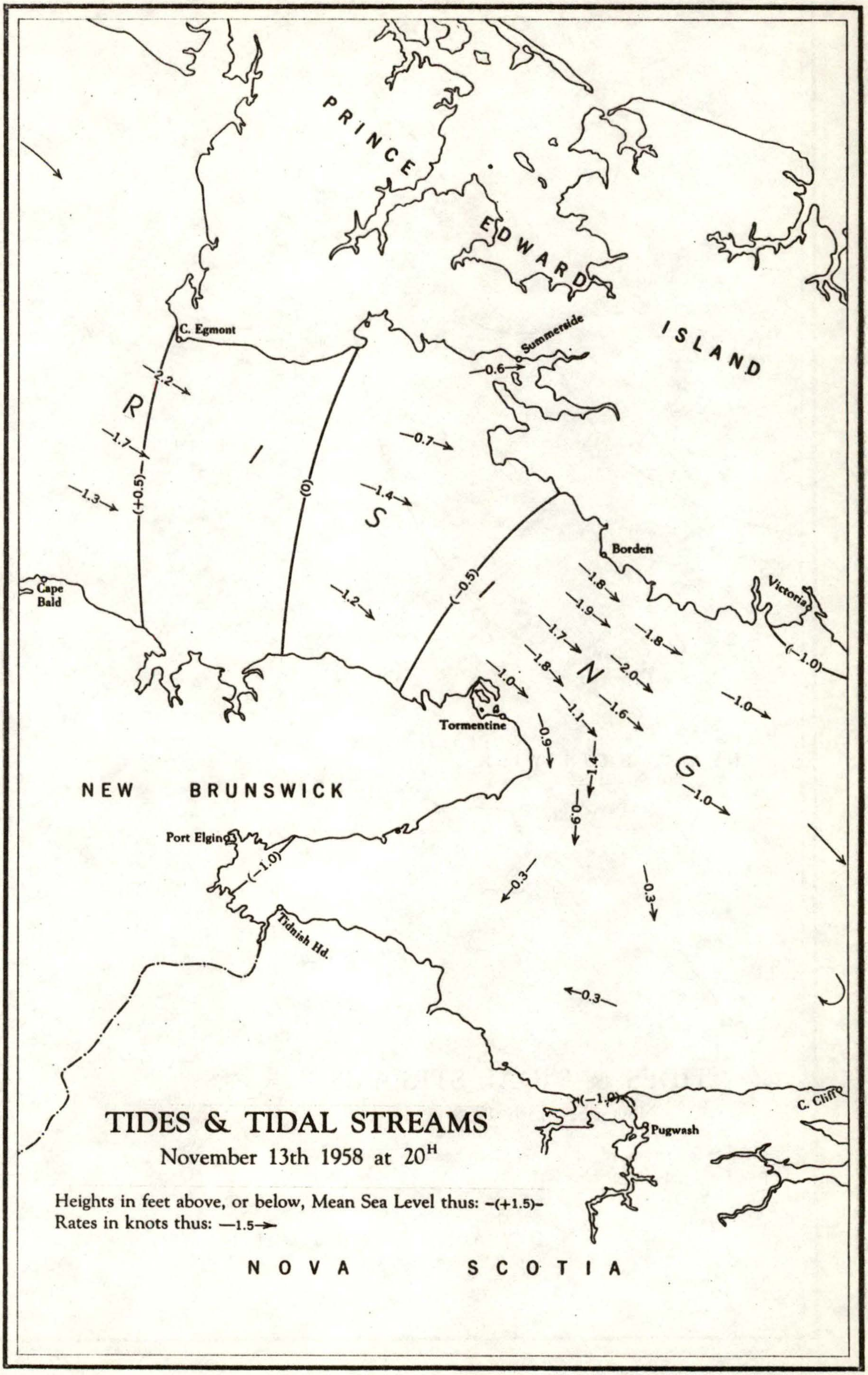

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
NEW BRUNSWICK
Port Elgin
Tidnish Hd.
C. Cliff
Pugwash
NORTHUMBERLAND STRAIT
NOVA SCOTIA
TIDES & TIDAL STREAMS
November 13th 1958 at 20^H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A.20

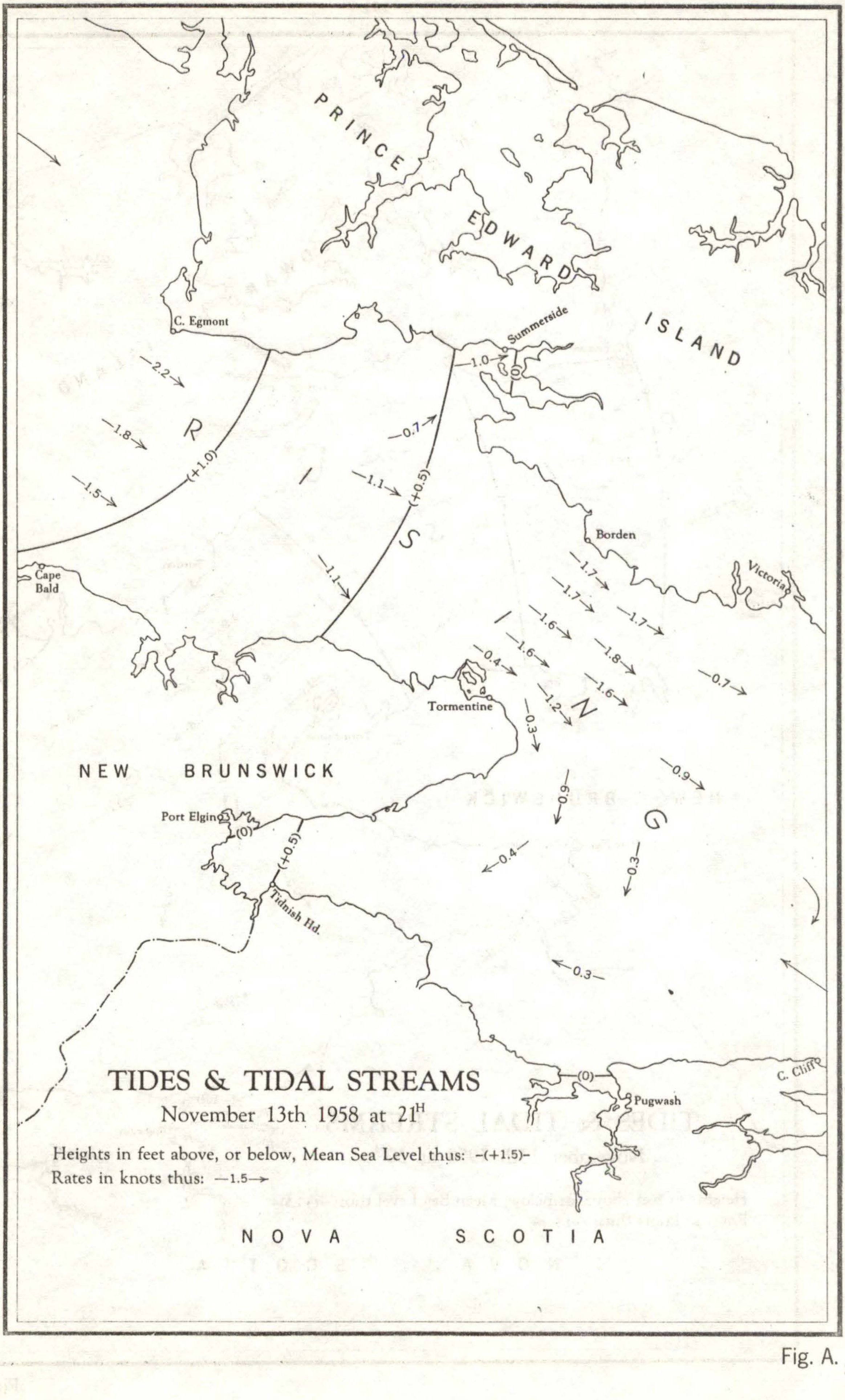

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
NEW BRUNSWICK
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
R I S I N G
(+1.0)
(+0.5)
(0)
2.2
1.8
1.5
1.0
0.7
1.1
1.1
1.7
1.7
1.7
1.6
1.6
1.8
1.6
0.4
1.2
0.3
0.7
0.9
0.9
0.4
0.3
0.3
TIDES & TIDAL STREAMS
November 13th 1958 at 21H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→
NOVA SCOTIA

Fig. A. 21

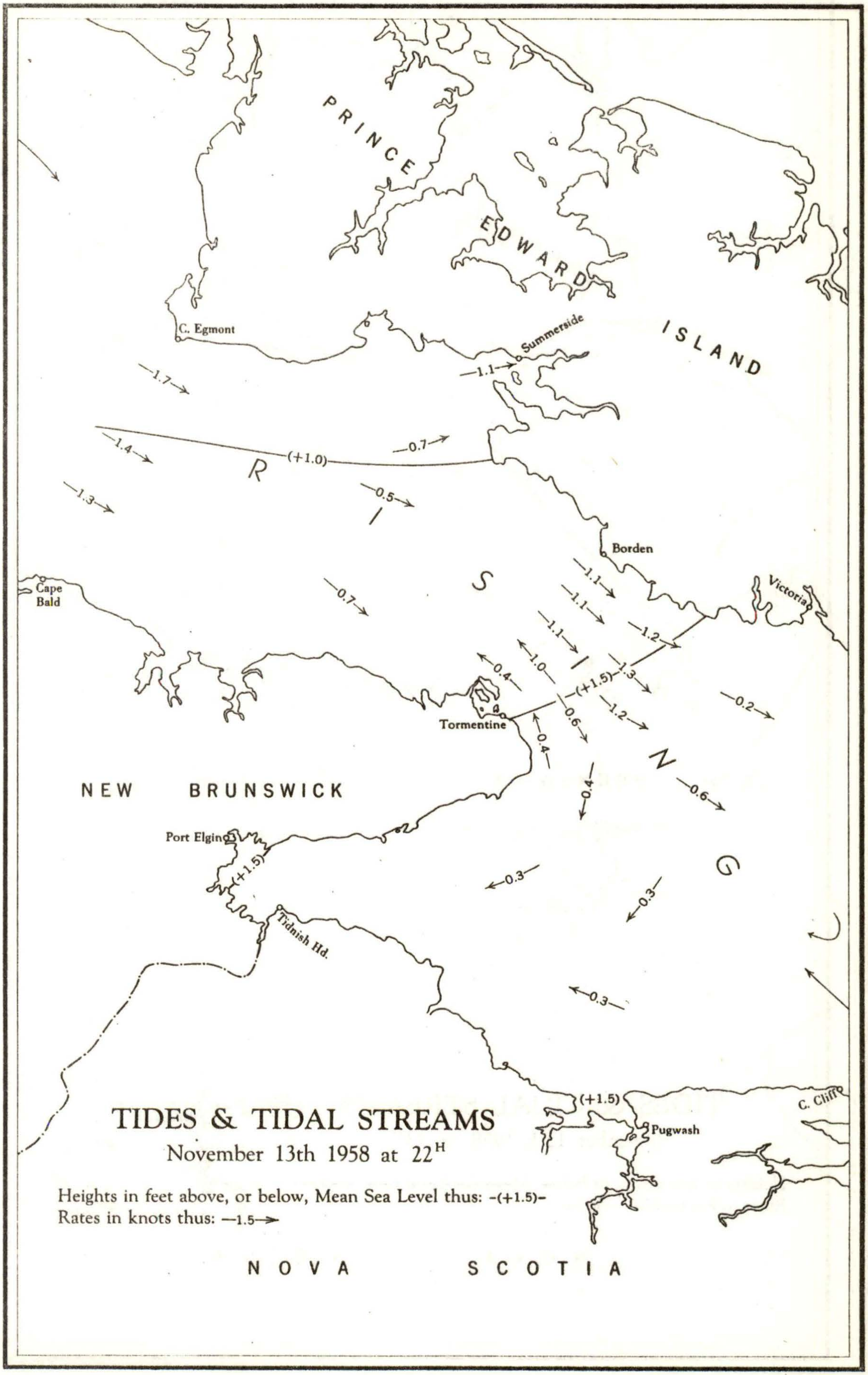

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
NEW BRUNSWICK
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
NOVA SCOTIA
R I S I N G
(+1.0)
(+1.5)
(+1.5)
(+1.5)
1.7
1.4
1.3
1.1
0.7
0.5
0.7
1.1
1.1
1.1
1.0
0.4
1.2
1.3
1.2
0.6
0.4
0.4
0.2
0.6
0.3
0.3
0.3
TIDES & TIDAL STREAMS
November 13th 1958 at 22^H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A. 22

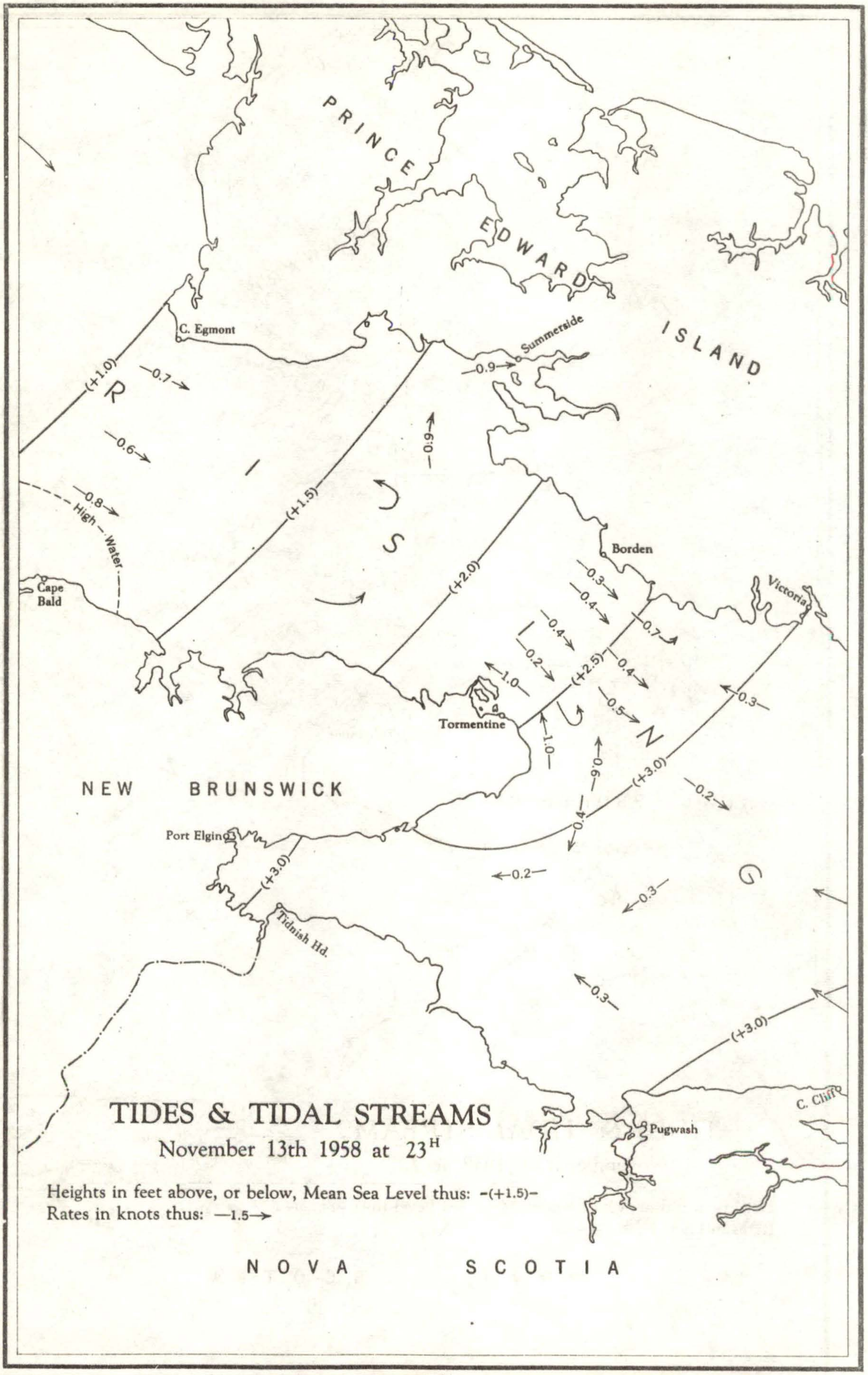
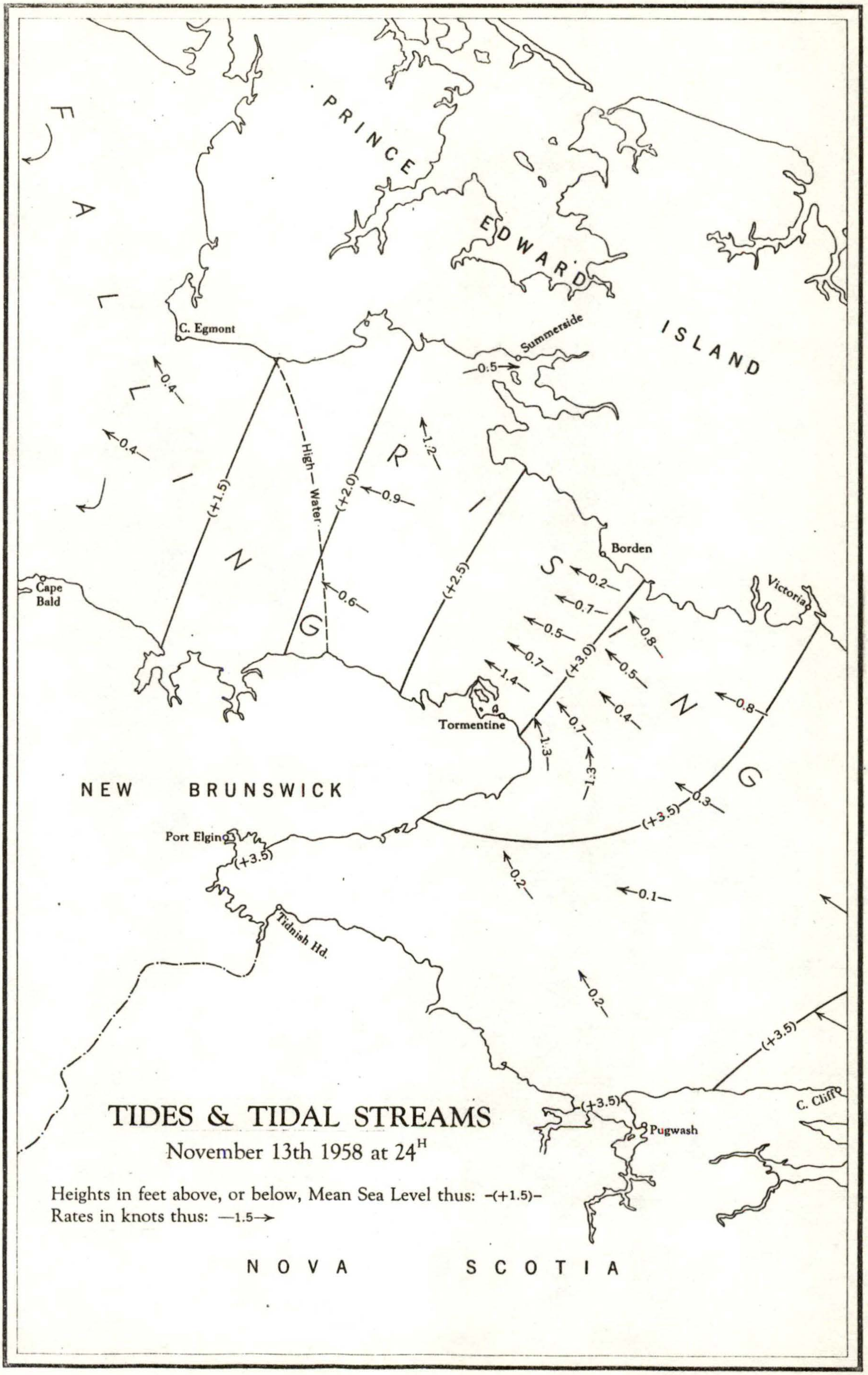

PRINCE EDWARD ISLAND
C. Egmont
Summerside
Borden
Victoria
Cape Bald
Tormentine
Port Elgin
Tidnish Hd.
Pugwash
C. Cliff
NEW BRUNSWICK
NOVA SCOTIA
R I S T I N G
High Water
(+1.0)
(+1.5)
(+2.0)
(+2.5)
(+3.0)
(+3.0)
(+3.0)
0.7
0.6
0.8
0.9
0.9
0.3
0.4
0.4
0.2
1.0
0.7
0.4
0.5
1.0
0.6
0.4
0.3
0.2
0.2
0.3
0.3
TIDES & TIDAL STREAMS
November 13th 1958 at 23H
Heights in feet above, or below, Mean Sea Level thus: -(+1.5)-
Rates in knots thus: —1.5→

Fig. A. 23



TIDES & TIDAL STREAMS

November 13th 1958 at 24^H

Heights in feet above, or below, Mean Sea Level thus: –(+1.5)–
Rates in knots thus: —1.5→

Fig. A.24

APPENDIX B 1

Liverpool Observatory and Tidal Institute.

August 1958.

Interim report on the effect upon the tidal regime in Northumberland Strait caused by the construction of a causeway between Tormentine and Borden.

1. GENERAL REMARKS ON THE PROBLEM

To determine the effect on the tidal regime in a body of water such as the Northumberland Channel by the introduction of a barrier near its centre is a problem which may be treated in two ways. It may be assumed that the channel is so narrow that transverse currents may be neglected, and we then have a one-dimensional problem which may be solved by the classical method of integrating from section to section along the channel's length. If the channel becomes sufficiently broad to permit appreciable transverse currents, the problem must be treated in two dimensions; the mathematical method of relaxation may here supply a solution.

Both methods have been used for the Northumberland Channel, but the final conclusions have been obtained from integrations in one dimension. Two dimensional relaxation was found to be inapplicable to a channel of such relatively small dimensions unless a prohibitive number of significant figures were used in the quantities representing tidal elevations.

Use has been made of a relaxation solution of the one-dimensional problem, however, as will be explained later.

2. TIDAL EQUATIONS

The equations governing the tidal movements in a narrow channel are

$$\frac{\partial}{\partial x}(Au) = -b\frac{\delta\zeta}{\delta t}$$

$$\frac{\partial u}{\partial t} = -g\frac{\delta\zeta}{\delta x} - fu$$

where ζ is the elevation above mean level

u the stream velocity in the direction of x increasing

h the depth, a function of x

b the breadth, a function of x

$A = b(\zeta + h)$ the cross-sectional area

g the acceleration due to gravity

f the frictional parameter

t time.

Representing ζ and u as simple harmonic terms of angular speed σ,

e.g. $$\zeta = H\cos(\sigma t - \alpha) = H_1\cos\sigma t + H_2\sin\sigma t$$

$$u = U\cos(\sigma t - \gamma) = U_1\cos\sigma t + U_2\sin\sigma t$$

where $H_1 = H\cos\alpha$, $H_2 = H\sin\alpha$, $U_1 = U\cos\gamma$, $U_2 = U\sin\gamma$

then the above equations may be transformed into the finite difference equations

$$\delta(AU_1) = -b\,\sigma\,\delta x\,.\,H_2 \qquad \delta(AU_2) = b\,\sigma\,\delta x\,.\,H_1$$

$$\delta(H_1) = -\frac{\sigma\,\delta x}{g}U_2 - \frac{f\,\delta x}{g}U_1 \qquad \delta(H_2) = \frac{\sigma\,\delta x}{g}U_1 - \frac{f\,\delta x}{g}U_2$$

Given U and γ at any section in the channel, and H and α midway between this section and one of its neighbours, these equations make it possible to compute the elevation and stream at all sections in the channel.

Preliminary calculations soon made it obvious that frictional effects could not be ignored in the Northumberland Channel, and a quadratic law of friction has been used. This leads to the customary expression $f = 0.002\ U/h$.

3. TIDAL ELEVATION DATA

The elevation data available for the investigation are in the form of harmonic constants obtained either by the Canadian Hydrographic Service or by the Tidal Institute, and are tabulated in Table 1* for the principal constituents M_2 and K_1. The reliability of the constants depends principally upon the number of days of observation analysed, and these are also indicated. The two phases of each of M_2 and K_1, defined by

$$H_1 = H \cos \alpha \qquad H_2 = H \sin \alpha$$

are plotted with reference to distance from the causeway site in Figures 1 and 2**, and a mean curve has been drawn. Some of the deviations from the mean may be attributed to the effect of the earth's rotation; thus in the eastern channel the values of H_1 and H_2 for Prince Edward Island are generally more negative than those for corresponding stations on the mainland. Other deviations may be attributed to geographical peculiarities; for example, due to its position up a shallow river, Pictou appears anomalous on the M_2 graph.

4. TIDAL STREAM DATA

When the investigation was commenced the only tidal stream data available consisted of three 15 days' analyses at stations b, d, and c (Figure 4***). The Canadian Hydrographic Service has subsequently obtained many observations using a Gurley meter at a depth of 7 m., and an Ekman meter near the bottom,

* Replaced by Table B1a, Appendix B2, page 123.
** Replaced by Figures B1a and B2a, pages 111 and 113.
*** The index to all tide and tidal stream stations is included in the main report as Figures 1a and 1b, pages 13 and 14.

in the eastern channel. The analytical results for M_2 are given in Table 2* . It will be seen that the bottom current is approximately 2/3 that at a depth of 7 m., and 15° in advance of it. The depth mean of current, taken as the unweighted vectorial mean of the two sets of results, is also given in the table .

5. RESULTS OF COMPUTATIONS

The validity of the integration method is first confirmed by reproducing the tides observed; the tides which will exist following the introduction of a causeway are then computed. Sections along the median line of the channel (Figure 3**) were taken at convenient intervals such that $\delta x = 11.9$ miles, with Section 0 at the causeway site. The values of h and b, obtained from the largest scale chart, are shown in Figure B5, page 117.

The part of the channel to the northwest of the barrier site was dealt with separately from that to the southeast. Streams have been taken as positive when directed away from the causeway.

<u>Western channel</u>

(a) Commencing with U = 1.13 knots, $\Upsilon = 4°$ at Section 0, $H_1 = 1.45$ ft., $H_2 = -1.30$ ft. at Section 0.5, and using unsmoothed values of h and b, the distribution of M_2 was computed and is shown in Figure 1***. These results are in good agreement with the smooth line drawn through the observed values , and in particular the gradients of H_1 and H_2 near the open end of the channel have been reproduced. The amount of scatter shown by the computed values is

* Omitted as incomplete.

** See Figure 1a in the main report, page 13.

*** Replaced by Figure B1a, facing.

CONSTITUENT M_2

OBSERVED AND COMPUTED VALUES

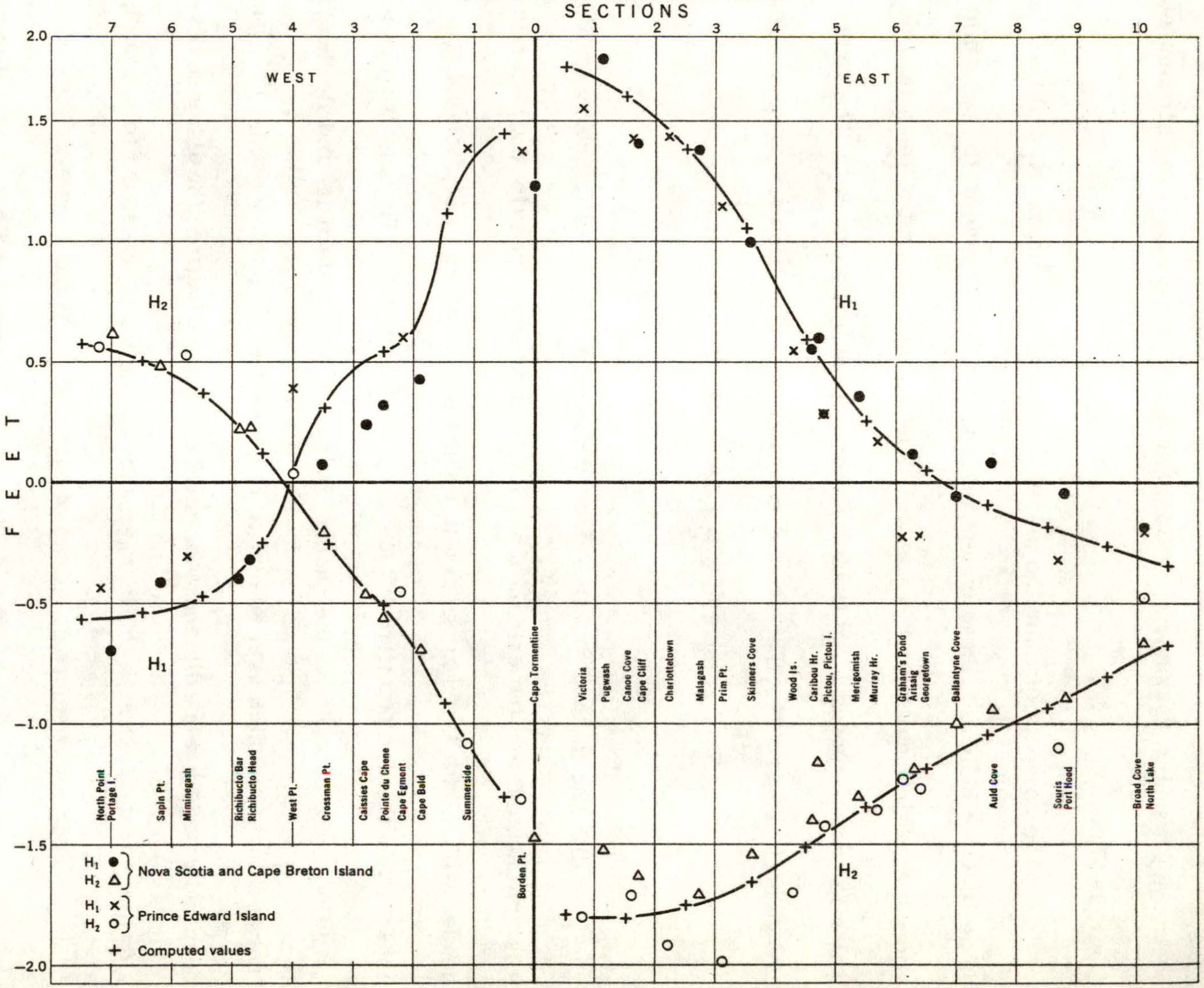


Fig. B1a.

less than that displayed by the observational data. The computed stream at Section 4. 0 was U = 1. 22 knots, γ = 23°, compared with an observed stream of U = 1. 09 knots, γ = 26°.

The computations for the principal diurnal constituent K_1 followed the same lines as indicated above except that the value of U used in the determination of the frictional term f, as is well known, must be that of the total tide, which for our purposes is sufficiently represented by that of M_2. The results are given in Figure 2*. The stream comparisons at Section 4. 0 are:-

computed U = 0. 28 knots, γ = 8°

observed U = 0. 25 knots, γ = 20°.

(b) The method was therefore considered highly satisfactory for the western channel, and the calculations for the causeway in position could be proceeded with. With U = 0 at Section 0, values of H_1 and H_2 at Section 0. 5 were chosen, and the computations effected out to Section 7. 5. The condition to be satisfied at the entrance to the channel is that the gradients of H_1 and H_2 should merge into those which existed before the causeway was introduced. This has been indicated by a one dimensional relaxation investigation; the distance outside the entrance at which the merger should take place was found to be small.

Successive approximations of H_1 and H_2 near the causeway site led to the results given in Figures 6 and 7**. Little change is indicated in the distribution of K_1, but for M_2 the picture is completely changed. The nodal point which exists in nature at Section 4 disappears. The range of tide throughout the channel is increased, and at the causeway there is a phase shift of 137°.

* Replaced by Figure B2a, facing.

** Replaced by Figures B6a and B7a pages 118 and 119.

CONSTITUENT K_1
OBSERVED AND COMPUTED VALUES

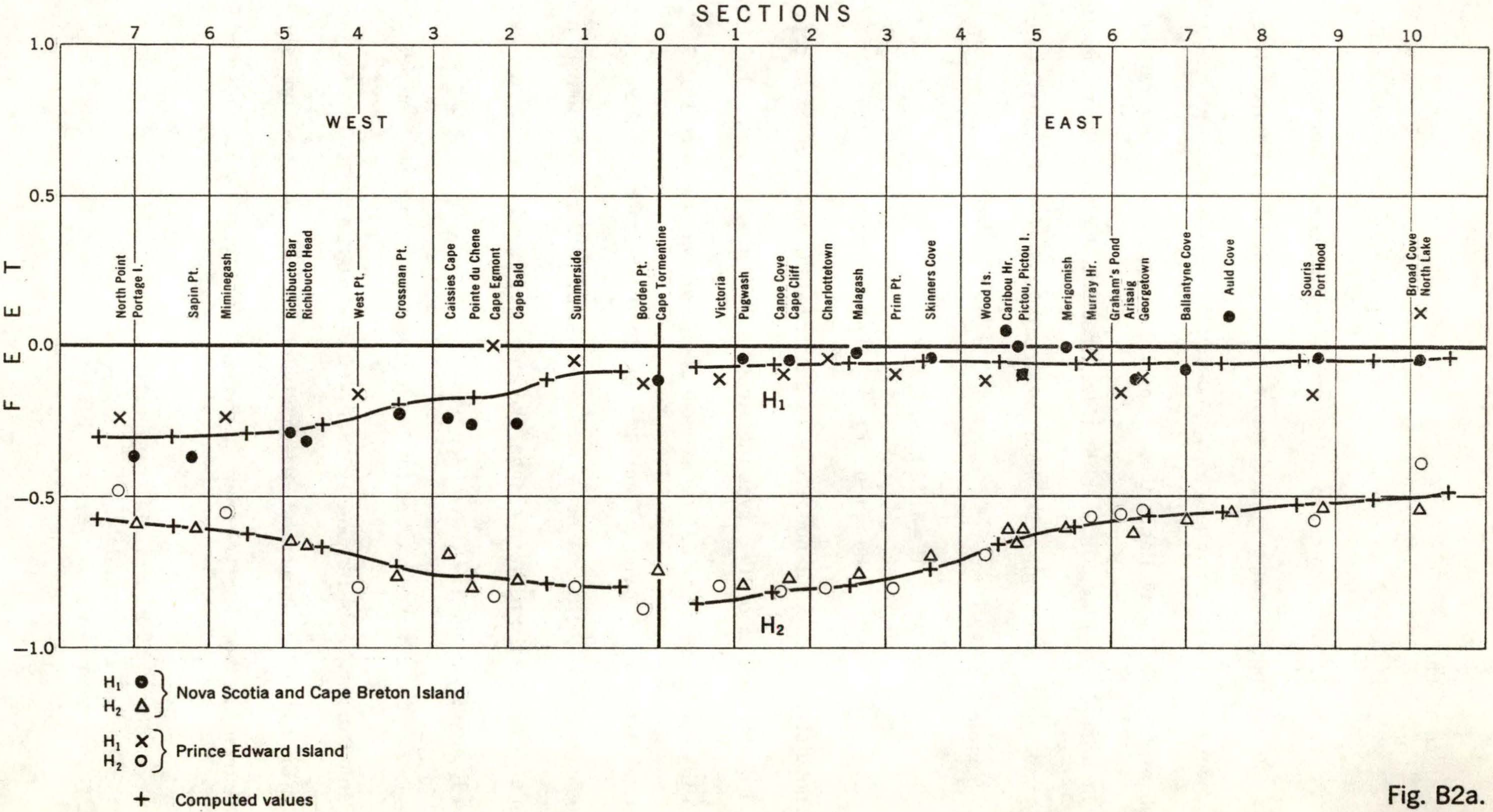


Fig. B2a.

Eastern channel

This part of the channel is much more irregular in breadth than the western part. The greatest variation occurs in the George Bay area and, what is more important, near the causeway site. It was found impossible to reproduce the elevations by integrating outwards from the causeway site using the observational data available there, and this is attributed to the rapid changes which must take place there in the tidal streams. Instead, the integration for M_2 was commenced using the observed streams at Section 4.0 and the elevations at Section 3.5, viz:-

$$U = 1.13 \text{ knots}, \quad \Upsilon = 68°$$

$$H_1 = 1.05 \text{ ft.} \qquad H_2 = -1.75 \text{ ft.}$$

These starting data did not give very good results, and in order to reproduce adequately the H_1 of H_2 curves the streams at Section 4.0 had to be changed to $U = 0.97$ knots, $\Upsilon = 52°$. The results are shown in Figure 1*. The computed streams are given in Table 2** and it will be seen that they are in good agreement with the depth mean values indicated by the Gurley and Ekman meters. In all work for the eastern channel the smoothed breadths and depths indicated in Figure B5, page 117, have been used.

The computed values for M_2 for the causeway in position are given in Table B1a (Appendix B2, page 123) and plotted in Figure 6***. The tide throughout the channel is increased, the maximum increase of approximately 1 foot occurring at the causeway where a phase shift of about 12° may also be noted.

* Replaced by Figure B1a, page 111.

** Omitted as incomplete.

*** Replaced by Figures B6a and B7a, page 118 and 119 respectively.

Calculations for the diurnal constitient K_1, with and without the causeway, are given in Figures 2* and 7**.

6. SUPPLEMENTARY INVESTIGATIONS

It was thought to be desirable to investigate some simple mathematical solutions for idealized basins as a supplement to the integrations for the actual basin. One such method was to investigate the theoretical solution in the absence of friction for an estuary of constant depth but with sides converging to a spot behind the causeway site so as to represent the western half of the strait, the open end being 4 times the width at the causeway site. The solution, in terms of Bessel's functions $J_0(Kx)$ and $Y_0(Kx)$, was obtained for two cases,

(a) with the causeway in position

(b) without the causeway but with a nodal line in the elevation at a point nearer the open end than the causeway site.

The results, while somewhat crude, demonstrated the important fact that the phase of the oscillation at the causeway in case (a) was the same as at the open end; that is, there was no nodal line with the causeway in situ such as there is without the causeway. Also tidal range at the causeway was given as about 2.4 times the tidal range at the open end.

In case (b) it was shown that the current existing at the causeway site was substantially the same as that existing in nature. It was evident that the existence of the nodal line in nature (without causeway) is due to the stream through the narrows at the causeway site. This was also proved by an independent investigation of two progressive waves, one proceeding westwards and the other eastwards, from the two ends of the strait.

* Replaced by Figure B2a, page 113.

** Replaced by Figures B6a and B7a, page 118 and 119, respectively.

Similar investigations for the eastern half of the strait showed that the phase was approximately the same as in nature.

These investigations were useful as confirming the general character of the changes made by the causeway, and indicated the reason for the disappearance of the nodal line in the western half and the consequent change of phase of tide at the causeway.

7. REMARKS ON THE SOLUTIONS

The final estimates of the distribution of M_2 and K_1 throughout the Northumberland Channel when the causeway is in position are given in Table B1a, Appendix B2, page 123. It should be emphasised that they depend essentially upon the tidal elevations occurring at the entrance to the channel; in all cases there is a magnification of the amplitude as the causeway is approached. Any error, therefore, in the tidal elevations at the entrances used in the calculations, would be magnified at the causeway.

At the causeway, using the results of Table B1a, the maximum difference in level between opposite sides, considering M_2 alone, will be of the order of 6 feet.

With regard to the other semidiurnal constituents not considered hitherto, a sufficiently accurate guide to their behaviour will be obtained by applying the amplitude factor and phase shift calculated for M_2. For the diurnal constituents the information for K_1 should be valid.

Some observational data have been received since the computations were completed; these have not affected the contents of this report.

DEPTHS AND BREADTHS IN NORTHUMBERLAND STRAIT

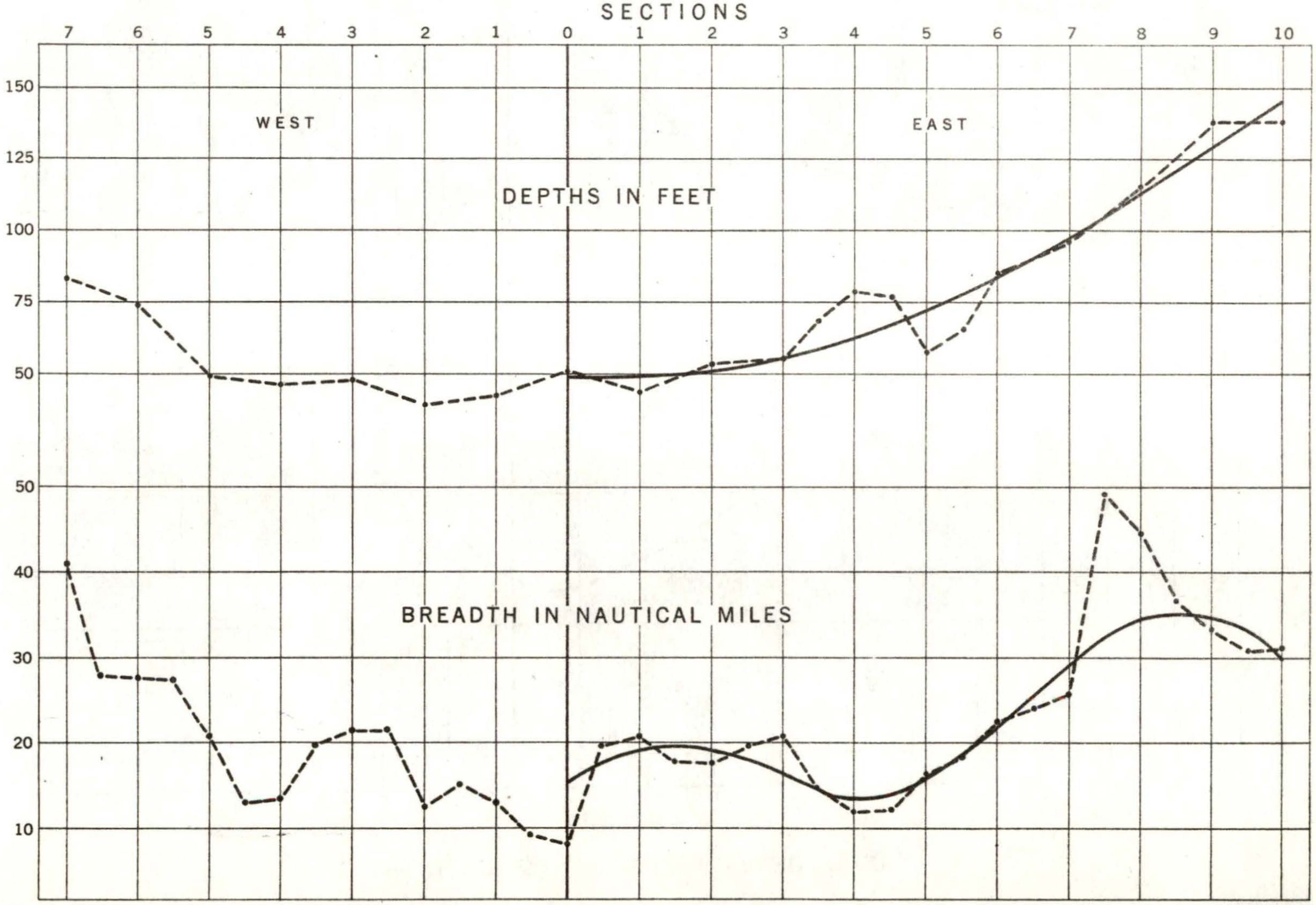


Fig. B5.

COMPUTED TIDES IN NORTHUMBERLAND STRAIT

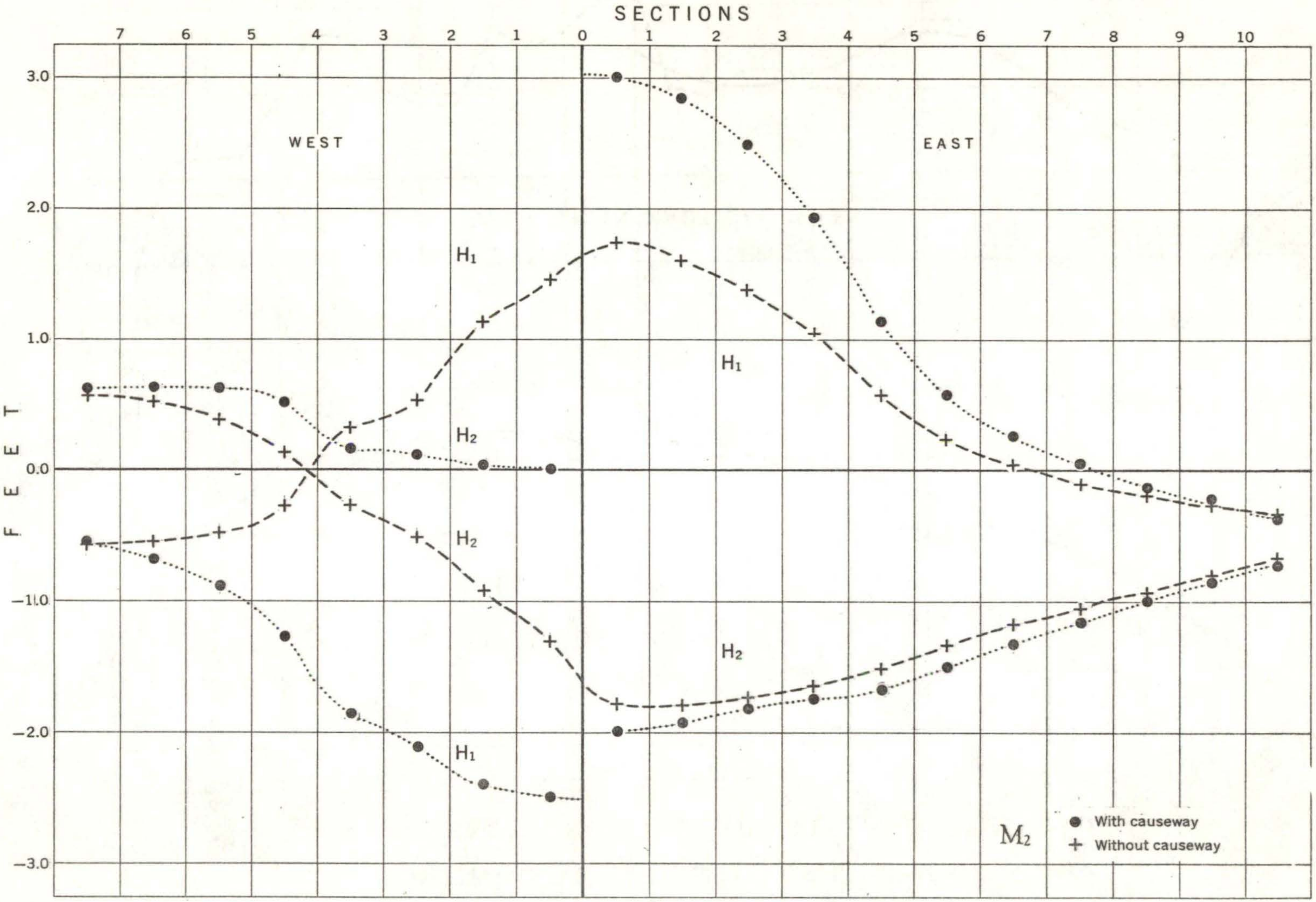


Fig. B6a.

COMPUTED TIDES IN NORTHUMBERLAND STRAIT

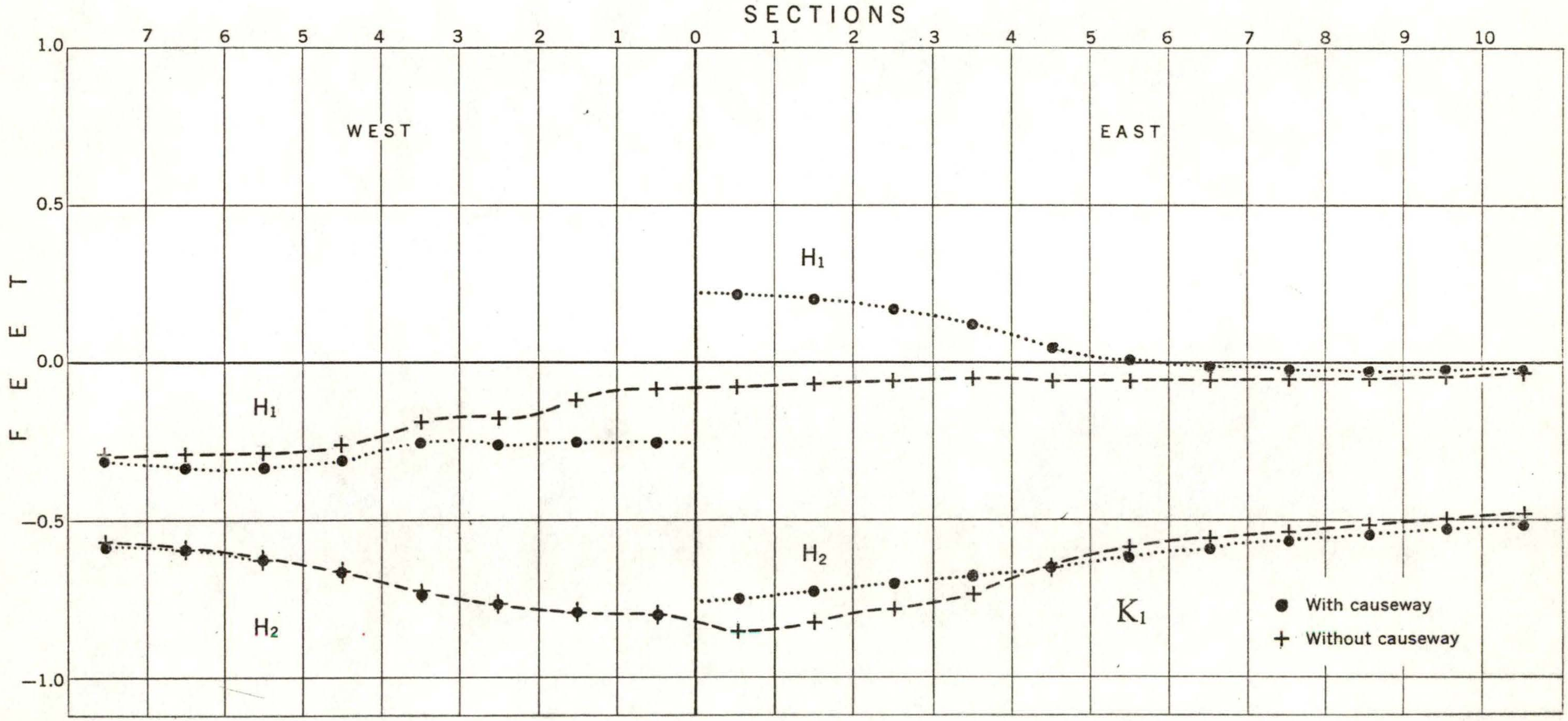


Fig. B7a.

APPENDIX B 2

Liverpool Observatory and Tidal Institute.

December, 1958.

Final report on the effect upon the tidal regime in Northumberland Strait caused by the construction of a causeway between Tormentine and Borden.

This final report does not replace the one submitted in August of the year, but should be considered as supplementary to it. The mass of new observational data, both for tidal elevations and streams, have necessitated only minor changes in the calculations of M_2 and K_1 without a causeway, and the enclosed Figures B1a and B2a (Appendix B1, pages 111 and 113) should replace Figures 1 and 2. The calculations for these constituents in the presence of the causeway have been slightly amended for K_1 for the eastern section, and the enclosed Figures B6a and B7a (Appendix B1, pages 118 and 119) should replace Figures 6 and 7.

1. The surface water gradients transverse to the main tidal stream have been calculated for M_2, S_2, and K_1, using observed stream data, and are in very good agreement with the observed gradients at all the major stations. The same principle was used with the data calculated for the case of the causeway in position, and the co-tidal and co-range charts* enclosed represent the results of this extension to the August report.

* See Figures 2b, 2c, 2e and 2f in main report.

2. The data for the three major constituents, with and without the causeway, are given in Table B1a (facing) for the major stations or harbours in the area. It is from these figures that the co-tidal and co-range charts have been constructed.

3. It has been requested that some estimate be given of the magnitude of possible disturbances in elevation on both sides of the causeway, due to local winds. The orientation of the channel is such that maximum raising of level will occur on the western side of the causeway with a wind from the north or north-west, and on the eastern side with a wind from the east or east-north-east.

The following table enables some idea of possible magnitudes to be expected*:

	West Section	East Section
Mean depth (ft)	55	75
Length from mouth to causeway (miles)	84	120
Period for resonance (hours)	11.7	14.4
Optimum direction for maximum wind effect	NNW	E by N

	V (m.p.h.)	Surge (ft)
Resulting elevations at causeway for winds	30	1.8
of varying strength, blowing in optimum	40	3.4
direction (both sections)	50	5.2
	60	7.5

The resonant period has been calculated from Equation 19.2b in the Admiralty Manual of Tides. If the period of the wind on any occasion approaches these figures, one would expect larger oscillations in the disturbances than are in-

* See also para. 8, Appendix C.

TABLE B1a

HARMONIC CONSTANTS BEFORE (OBSERVED) AND AFTER (COMPUTED) INTRODUCTION OF CAUSEWAY

	M_2				S_2				K_1			
Place	Before		After		Before		After		Before		After	
	H	g	H	g	H	g	H	g	H	g	H	g
Sapin Point	0.64	131	1.1	131	0.16	169	0.3	198	0.69	239	0.7	239
Miminegash	0.61	119	0.9	148	0.21	182	0.2	207	0.60	246	0.7	246
Richibucto Bar	0.45	150	1.4	141	0.13	180	0.4	207	0.68	247	0.7	239
West Point	0.40	4	1.6	176	0.20	98	0.4	243	0.82	259	0.8	251
Crossman Point	0.22	287	1.8	167	0.10	90	0.6	231	0.77	255	0.8	248
Caissies Cape	0.52	296	2.0	171	0.14	29	0.7	243	0.75	251	0.8	249
Pointe du Chene	0.65	301	2.1	172	0.13	32	0.7	236	0.84	252	0.8	248
Cape Egmont	0.76	324	2.2	180	0.19	66	0.8	247	0.82	270	0.8	253
Cape Bald	0.81	302	2.3	175	0.16	34	0.8	247	0.81	252	0.8	251
Summerside	1.76	322	2.4	178	0.36	43	0.9	249	0.78	267	0.8	253
Borden Point	1.92	316	2.5	180	0.47	26	0.9	249	0.88	262	0.8	253
Cape Tormentine	1.92	310			0.48	33			0.74	263		
Port Elgin	2.37	324	3.6	335	0.55	45	0.7	44	0.84	278	0.8	296
Tidnish Head	2.40	311	3.6	325	0.53	24	0.7	34	0.83	267	0.8	287
Victoria	2.37	311	3.7	325	0.66	22	0.7	34	0.81	262	0.8	285
Pugwash	2.34	319	3.5	327	0.56	30	0.7	34	0.79	268	0.8	289
Canoe Cove	2.23	310	3.4	322	0.54	20	0.7	34	0.81	265	0.8	282
Cape Cliff	2.16	311	3.4	330	0.39	24	0.7	34	0.78	267	0.8	288
Charlottetown	2.40	307	3.3	320	0.61	11	0.6	31	0.82	267	0.7	281
Malagash	2.20	309	3.0	330	0.47	13	0.6	39	0.72	269	0.7	288
Prim Point	2.30	300	2.9	316	0.51	15	0.6	31	0.81	264	0.7	277
Skinners Cove	1.83	303	2.5	323	0.39	16	0.4	27	0.70	268	0.7	283
Wood Islands	1.79	288	2.2	302	0.38	349	0.4	14	0.66	260	0.7	272
Caribou Harbour	1.50	292	1.8	311	0.29	350	0.4	14	0.61	276	0.6	277
Pictou	1.28	295	1.8	317	0.36	348	0.3	19	0.68	271	0.6	282
Pictou Island	1.45	281	1.8	299	0.37	345	0.4	0	0.60	260	0.6	274
Merigomish	1.35	286	1.4	309	0.29	349	0.2	0	0.60	270	0.6	279
Murray Harbour	1.37	277	1.7	280	0.36	339	0.3	341	0.56	268	0.6	266
Graham's Pond	1.25	260	1.7	277	0.33	318	0.4	326	0.57	254	0.6	264
Arisaig	1.19	276	1.2	299	0.29	322	0.2	0	0.63	261	0.6	274
Georgetown	1.29	260	1.6	270	0.37	317	0.3	315	0.55	261	0.6	262
Ballantyne Cove	1.00	267	1.0	287	0.25	312	0.2	333	0.57	263	0.6	272
Auld Cove	0.74	275	0.9	290	0.29	330	0.2	0	0.54	282	0.6	276
Port Hood	0.90	267	0.8	270	0.25	305	0.1	315	0.52	268	0.5	272
Souris	1.15	253	1.3	252	0.29	304	0.3	315	0.60	255	0.6	262

dicated at the end of the table. The latter figures have been calculated from the well established formula

$$\delta\zeta = \frac{nk}{gh}\,\frac{\rho_a}{\rho}\,V^2\,\delta x$$

which may, for instance, be found in R. H. Corkan's Royal Society paper No. 853, 4 July, 1950. The values used in this instance are

$$n = 1.25, \quad k = 2 \times 10^{-3}, \quad g = 32 \text{ ft/sec}, \quad \frac{\rho_a}{\rho} = 1.2 \times 10^{-3}$$

The table indicates that for a wind blowing towards the causeway with an average value of 50 m. p. h., the ultimate steady elevation above the normal tidal level at the causeway will be of the order of 5 ft. in either section of the channel. If the wind is directed away from the causeway, under the same circumstances there will be a lowering of level of the order of 5 ft. For winds the mean direction of which are not directly along the channel, the values in the tables would need to be multiplied by the cosine of the angle between the actual wind direction and its optimum direction.

4. We regret that we cannot give a specific reply to the question of how the amphidromic point in the western section will disappear as the causeway is built out into the channel. The problem is complicated by the rapid changes which take place in the distribution of the tidal streams near Cape Tormentine, and none of the simple computational devices we have tried have provided a satisfactory solution.

The amphidromic point exists solely as a result of the fact that the tidal wave from the western entrance, travelling eastwards, and the tidal wave from the eastern entrance, travelling westwards, happen, in one area, to possess the same amplitude and opposite phase. This is a coincidence, and it would seem to us that when the degree of penetration allowed these waves through the Tormentine narrows is reduced by the construction of the causeway, the amphidromic point will quickly disappear and be replaced by an area of small range which will fill up.

5. In conclusion we wish to emphasise the basis upon which calculations of the tidal regimes with the causeway erected have been made. We have assumed, with the support of investigations referred to in §1 of our August report, that the elevations at the entrances will remain substantially unaltered by the introduction of the causeway. It then transpires that the M_2 current at Section 7 of the western section will be altered 116° in phase and doubled in amplitude compared with the current without the causeway. It may be argued that this result is unreasonable, but the alternative, that of attempting to keep the current at the mouth unaltered by the introduction of the causeway, is even more so. Calculations show that such a basis for calculations would make considerable changes in the distribution of the elevation out into the Gulf of St. Lawrence, and it is most unreasonable to expect that such a relatively small body of water as the Northumberland Channel could appreciably affect the tides in the larger body. Our explanation of the large change in phase quoted above is that if it were computationally possible to extend the calculations beyond Section 7, the currents with and without the causeway would converge, as do the elevations.

APPENDIX C

Liverpool Observatory and Tidal Institute.

February, 1959.

Storm Surges in the Gulf of St. Lawrence, 28 September to 1 October, and 28 November to 5 December, 1958.

The data sent to us for investigation comprised residual (observed minus predicted heights of tide) and synoptic charts. The latter provided a picture of the pressure and wind distribution at any time for the area concerned, whilst the residuals indicated the changes in level taking place in the Northumberland Strait most clearly, but have failed to give a sufficiently comprehensive indication of the changes in the Gulf of St. Lawrence as a whole.

1. The data show that a depression travelling northwards along the Atlantic seaboard generates a surge which penetrates Cabot Strait and apparently spreads out into the Gulf in all directions (see data for Sept. 29 and Nov. 29). The times taken for the surge to travel from Port aux Basques and Sydney to Northumberland Strait are in accord with what might be expected from theory, and it will be noted that the peaks quoted are all much the same in magnitude. Levels are high in the Gulf at approximately the same time, indicating an influx of water from the Atlantic. The calculated times of travel for a free progressive wave from Cabot Strait to the causeway site via the eastern section of Northumberland Strait is about 2. 5 hours, and via the western section, 3. 5 hours. In the absence of a causeway, these two waves mix with each other in the Strait, and the difference in time of arrival at the causeway site is so small as to generate a negligible surface gradient, and hence a negligible current through the causeway section. The presence of a barrier will prevent mixing, but again, the small

difference in time of arrival at the barrier will mean only a small difference in levels on its opposite sides. Due to the mixing of the waves in the Strait it has been found impossible to confirm the above quoted times of travel to the causeway site, but the times of travel from Cabot Strait to the ends of Northumberland Strait are of approximately the right order.

2. Examination of the residuals shows that winds in the Gulf of St. Lawrence can cause water gradients to develop in the direction of the wind (e. g. Sept. 29 a. m.; levels low at Harrington due to northerly winds over the Gulf). A much more pronounced effect, however, is the lowering of level following nearly every positive surge. These do not appear to be associated with any common wind field, but would appear to be the result of an outflow of water from the Gulf area as a whole. The lowerings are a minimum at Cabot Strait, which suggests that along the Strait is a nodal line about which the oscillations take place. The general picture is thus built up, for these types of surges, of an influx of water into the Gulf area, spreading out in all directions and generated by the passage of a depression up the coast. As the depression travels away or is weakened, normal levels are gradually attained by means of a standing oscillation with the nodal line near Port aux Basques and North Sydney.

3. One further interesting phenomenon has appeared from the study of the residuals concerning the period Sept. 28 to 30. The meteorological data at our disposal indicates no reason for the existence of the positive surge of Sept. 30. The timing of the maxima show a definite progression from west to east through the Strait. The only theory we can put forward for this peak is that it is the next in the oscillation set up originally on the 29th. The concept of inertial

oscillations has been proposed in the preceding paragraph to account for the type of lowering experienced during the night of Sept. 29/30, and the return of water through Cabot Strait from the Atlantic could well be envisaged entering the Gulf and, under the influence of the earth's rotation, travelling around the Gulf in an anti-clockwise direction. Support for this theory may be found in the time of the maximum peak at Harrington (approximately 4 a. m. on the 30th) as compared with its arrival at Point Sapin (approximately 9 a. m.).

4. The foregoing remarks on the general nature of the residuals sent to us for study have been set out to illustrate the complicated nature of storm surge phenomena in the Gulf of St. Lawrence. This is an important point, for it has made the task of determining the wind-driven current in the Strait, due to local winds, from observations, virtually impossible. It means that only conditions generated by a stationary isobaric system could possible be suitable for such a determination, and none of the data provided conform to this condition. Moreover a considerable number of examples of this type would need to be investigated.

To provide estimates of the wind-driven current generated by local winds it is therefore necessary to rely upon the results of observations taken by other workers. One of the most quoted investigations into this problem is by Palmen who, from observations in the Gulf of Bothnia, found the relationship

$u_o = bV$, where u_o is the surface current, and V the surface wind velocity, and $b = 0.014$.

From data for the west coast of America, off the west coast of Africa and also off the east coast of Africa, Thorade found a coefficient of 0. 013. With data for the north Atlantic and Indian oceans Durst found a coefficient of 0. 008. In Marmer's paper 'Coastal currents along the Pacific Coast of the United States' may be found the results of thousands of observations of wind and wind-driven current. All these may be summarised in the following table:

Wind Velocity in Knots	Surface Velocity of Water in Knots			
V	u_o			
	Durst	Thorade	Palmen	Marmer
10	0.08	0.13	0.14	0.22
20	0.16	0.26	0.28	0.44
30	0.24	0.39	0.42	0.64
40	0.32	0.52	0.56	0.81
50	0.40	0.65	0.70	0.94

For the Gaspé coast Bell Dawson in his 1913 report on "The currents in the Gulf of St. Lawrence" states that for winds of an average velocity of 25 m.p.h. the wind-driven current is of the order of 3/8 of a knot, which is equivalent to a value of 0.017 for the coefficient b. All these values are in fair agreement for a relationship about which we really know very little, and on which much thought and energy is being expended by many oceanographers.

5. On page 165 of "The Tide" Marmer probably best sums up our knowledge of this subject by writing 'In fact, a general rule has been formulated for the benefit of the mariner which states that along the Atlantic and Pacific coasts of the United States, say from 5 to 20 miles offshore, the velocity of a current produced by a wind is about 2 per cent that of the wind.........'

6. In the light of the foregoing remarks it would be wrong to suppose that the only current additional to the tidal stream is that produced by local winds.

The disturbances described above, generated in the Atlantic or the Gulf of St. Lawrence, will also be accompanied by surge currents, and the possibility of estimating their magnitude, using the residuals available, was examined.

The equation of motion which governs the flow of water in a channel may be written so as to include both tidal and surge currents. Assuming a knowledge of the tidal current and of the laws of friction at both the top and bottom of the water column, it becomes possible to calculate the surge current if observations of the difference in surge height along a section of the channel and observations of the wind velocity and direction are known. Taking the section between Borden and West Point, this method was applied for the period September 28 to October 1. In the absence of wind observations the frictional effect of the wind during the period was neglected; this was a reasonable procedure, for the winds at this time were either light and directed along the channel, or strong but transverse to the channel. The results indicated a residual current which tended to lag behind the surge height graphs by a few hours, and which had maximum values of the order of 1 to 1. 5 knots. A possitive surge in the Strait was associated with a west-going current, and a negative surge with an east-going current. The other period for which residuals were available was not treated in the same manner, since it was not considered that the local wind effect could reasonably be ignored. It should be emphasised that to attain a worthwhile accuracy in the residual current the surface elevation gradient and the local winds must be known to a high degree of accuracy, and it is considered that further attempts to refine the method with the data in our possession could not be justified.

7. We are therefore in the position of being unable to give any upper limit to the strength of residual current which might be experienced in the causeway section due to abnormal weather conditions. It would seem fairly clear that currents of up to 2 knots might reasonably be expected under adverse conditions.

8. One further remark has suggested itself to us in regard to paragraph 3 of our report of December, 1958 [App. B2] concerning the steady-state levels which could be built up on either side of the causeway by winds. Examination of the geography of the Strait shows that the only straight section of the Strait lies between West Point and Pictou, and that the distances of the causeway from these sections should replace the distances of the causeway from the mouths of the Strait, which were used in computing the surge elevations. For this straight section the optimum wind direction would be W 30° N or E 30° S, and the surge heights given in the table of paragraph 3 would be reduced by a factor of three quarters for each section. It should be emphasised, however, that this reduction only applies to a uniform wind field in which the isobars are sensibly straight. The isobaric curvature associated with a depression to the north of the area under discussion could well coincide with the curvature of the Strait, in which case the values in paragraph 3 would be valid.

LIVERPOOL OBSERVATORY AND TIDAL INSTITUTE

Dear Farquharson:

I shall try to answer your queries of February 13th concerning our report on storm surge observations.

1. The surge of Sept. 29th may not be a good one from which to draw conclusions such as you have done. For some time before 8 h on that day strong winds had been blowing in a direction calculated to raise the levels at the eastern end of Northumberland Strait rather than at the western end, and it is likely that observations at Richibucto and Sapin Pt. do not solely represent the effect of a wave coming in from the Atlantic. The difference of two feet between the peaks at these two places may therefore not be typical of 'external' surges. I agree that the word small needs qualifying, but our difficulty is in knowing what data to use for the qualifications. Frankly we have none, and we can only guess. In any case, the answer to this question would depend upon the magnitude of the surge as it comes in through Cabot Strait, and here again we have no upper limit.

2. A surge at the barrier would seem possible from three causes; by winds in Northumberland Strait, by winds in the Gulf of St. Lawrence, and by propagation from the Atlantic. In the latter group I would also include the peculiar surge of Sept. 30th, mentioned in para. 3 of our report, and also any subsequent oscillation giving rise to a negative surge. For the first group we have already given estimates of possible surge height at the barrier, and some further comments are made in the next two paragraphs. For the second group we see no way of making an estimate of the surge height at the barrier without a very extensive investigation. As for the third group, which consists essentially of

travelling waves, we doubt if theory is of any assistance in determining the magnification in amplitude between Cabot Strait and the causeway site. As you well remember, Corkan found that external surges in the North Sea behaved in much the same way as the diurnal tide, but so far as we can see there is no fundamental theoretical reason why that should be so. Here again, I am afraid, a thorough investigation would be needed, which could only be done when the causeway is put up. All of which is no help to you I know!

3. The reference of a reduction of surge height by a factor of three-quarters most certainly intended our original figures to be replaced by three-quarters of their values, but I agree that there is perhaps some ambiguity in the way I put it.

4. We have gone over the figures we gave for the effect of local winds in raising levels at the barrier, but can only confirm that they truly represent the theory used. As a matter of fact, we have recently had a Russian oceanographer studying here with us, and he became interested in the problem (his line is oceanic currents) and by a much more elaborate method than we used produced almost identical figures.

I am sorry that we appear to be so unhelpful, but we simply cannot extract more out of the available data than we have. I do not agree that a causeway will have little or no influence in increasing heights at the causeway during a local storm, though I should not be surprised to find that travelling surges were not appreciably magnified by the introduction of a causeway.

The Observatory,
Birkenhead,
Cheshire,
ENGLAND.
February 18th, 1959.

APPENDIX D

OCEANOGRAPHIC OBSERVATIONS IN NORTHUMBERLAND STRAIT

Report by Atlantic Oceanographic Group

M.V. "Theta"

August 14 - September 20, 1958

Introduction

During the summer, the waters of the southwestern Gulf, including Northumberland Strait are stratified, as to temperature and salinity. Two layers are present in the area, where the waters are deep enough. The surface layer is relatively warm, isothermal and of low salinity. It is separated from a cold layer of relatively high salinity by a zone of steep vertical gradients of temperature called thermocline. Usually the thermocline coincides with the halocline, a zone of steep vertical gradient of salinity.

Some features of the surface layer and of the cold water layer are described in sections 12 and 13 of the "Report of the Atlantic Herring Investigation Committee", Bulletion No. 111 of the Fisheries Research Board of Canada. Some variations of temperature and salinity in shallow waters of the southwestern Gulf and the distribution of bottom temperatures are given in section 14 and 15 of the same report.

Results

The data collected from the "Theta" in August-September, 1958, were taken in "pairs", at two stages of the tide. Observations were made at 1 metre and near the bottom.

1. In general, the results of temperature and salinity at one metre and on the bottom show little variation between stages of the tide.

2. As shown by BT traces there are very little variations in the thickness of the surface layer between stages of the tide.

3. There are local variations in the thickness of the surface layer. The variations between the western and the eastern entrances to Northumberland Strait are partly temporal. Stations L-2 to L-4 were visited on August 15-18 and the stations AB-2 to AB-4, on September 18-20.

4. With respect to stratification, all the stations could be grouped as follows:

(a) Two-layer system: warm surface layer of low salinity and cold bottom layer of relatively high salinity, separated by a sharp boundary (thermocline). Stations: L-2 to L-4; AB-2 to AB-4.

(b) Two-layer system: warm surface layer of low salinity and cool bottom layer of salinity slightly higher than at the surface. The boundary between the two layers shows gradual changes of temperature as opposed to the sudden changes observed in case (a). Stations: K-1, F-3, F-4.

(c) One-layer system: warm surface layer of low salinity down to within a few metres from the bottom. The temperature is slightly decreasing near the bottom. Stations: F-2, G-2, FG-1.

(d) One-layer system: warm surface layer of low salinity to the bottom. Stations: J-1, J-3, G-3 to G-5, I-1, I-3, FG-2 and FG-3.

5. The two-layer system is generally found, at that time of the year, in deeper waters as opposed to the one-layer system in shallow waters.

Conclusion

The distribution of properties in the eastern half of the Strait and the stratification at the eastern entrance infer an estuarine type of circulation with an upstream net flow in the lower layer and a seaward net flow in the upper layer.