TIDAL TRANSPORTS AND STREAMS IN THE ST. LAWRENCE RIVER AND ESTUARY(*)

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ABSTRACT

Seven harmonic constituents (M_2, S_2, N_2, K_1, O_1, M_4 and MS_4) of the tidal transports and streams through each of 22 sections across the St. Lawrence river and estuary are calculated from water level data and the principle of continuity. Excellent agreement is obtained with values of the same harmonic constituents deduced from direct current measurements in four of the cross-sections. It is suggested that the average tidal streams through the sections are more accurately determined from the tide gauge data and the principle of continuity than could be accomplished by direct current measurement.

INTRODUCTION

The principle of continuity makes it possible to calculate the transport through any cross-section of a channel from a knowledge of the changes in the surface elevation along the channel and the transport through a single cross-section. This principle was used by FORRESTER (1967) to calculate the average M_2 tidal stream in a cross-section of the St. Lawrence estuary near Pte. au Père for comparison with the value observed directly with current meters. The good agreement obtained indicated that it would be valuable to calculate similar information for other cross-sections and for other tidal constituents in addition to M_2.

During the summer of 1967 the Tides and Water Levels Section of the Canadian Department of Energy, Mines and Resources had in operation a network of about 20 additional temporary tide gauges in the estuary between Québec and Pte. au Père (figure 1). The availability of this new

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tidal data below Québec to supplement that already available above Québec persuaded the author to prepare tidal transport and average tidal stream information for various cross-sections between Lake St. Peter and Pte. des Monts.

METHOD

For the purposes of this study tidal movements are considered to be negligible above the head of Lake St. Peter, which provides the boundary condition that tidal transports have zero amplitude at this cross-section. To carry out the continuity calculations the river and estuary were divided into 22 regions as delineated in figure 1. The surface area of each region at mean water level was scaled from Canadian Hydrographic Service charts. The regions and also their surface areas are referred to as A_i, i being the number of the region. The area of the vertical cross-section at the down-stream end of each region was also determined from the charts. The downstream cross-sections and also their areas are referred to as a_i. From the tide gauges, values of the harmonic constituents M_2, S_2, N_2, K_1, O_1, M_4, and MS_4 of the vertical tide were assigned to each region; where more than one tide gauge was taken to represent a region, a vector average was employed. The symbols H_i and g_i (of M_2, etc.) are used to denote the amplitude and phaselag respectively of the constituents of the vertical tide in the i^{th} region. Figure 1 shows the regions and cross-sections treated, along with the locations from which tide gauge information was obtained. Where information from one tide gauge was used in two regions this has been shown by arrows pointing from the gauge to the two regions. The prefix "T" identifies the temporary gauges placed in 1967.

The harmonic constituent of tidal volume above cross-section a_n is denoted as having amplitude V_n and phaselag G_n (of M_2, etc.). Thus,

$$(V_n\, ,\, G_n) = \sum_{i=1}^{n} (H_i A_i\, ,\, g_i) \tag{1}$$

the summation being carried out vectorially.

The harmonic constituent of tidal volume transport through cross-section a_n is the time derivative of (V_n, G_n) and is denoted as (U_n, J_n). Thus,

$$(U_n\, ,\, J_n) = \frac{d}{dt}(V_n\, ,\, G_n) = (\omega V_n\, ,\, G_n - 90°)\ , \tag{2}$$

where ω is the angular frequency of the constituent (M_2, etc.).

The corresponding harmonic constituent of the average tidal stream through cross-section a_n is obtained by dividing the tidal volume transport by the cross-sectional area, so

$$(v_n\, ,\, K_n) = \left[\frac{U_n}{a_n}\, ,\, J_n\right]\ . \tag{3}$$

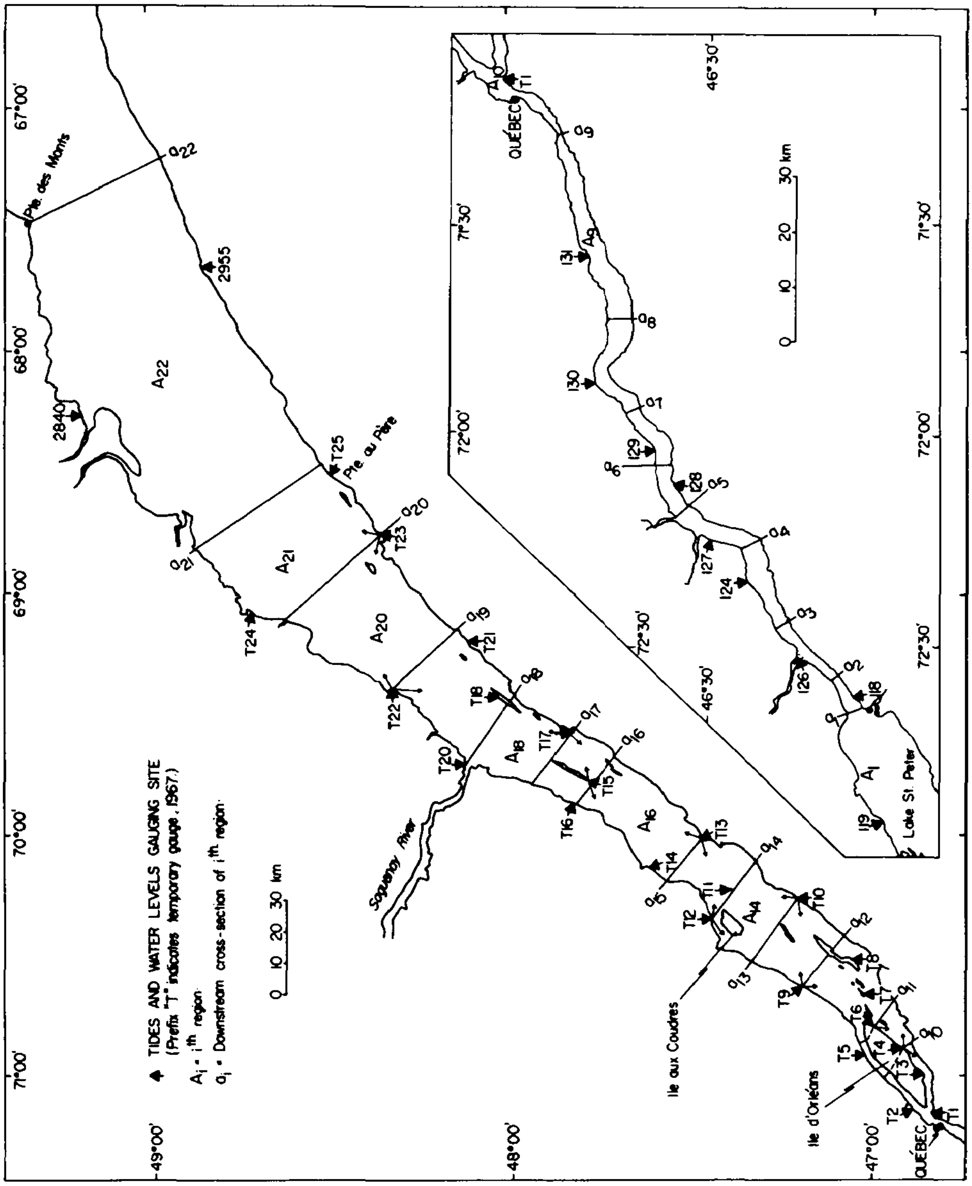

FIG. 1. — Regions and cross-sections of St Lawrence river and estuary, showing tide gauge locations.

Values of the average river discharge volume through the various cross-sections and the corresponding average river current were estimated for comparison with the tidal volume transports and tidal streams. The discharge values came from a variety of sources and are only approximate. The actual river discharge is subject to considerable variation through changes in run-off and water level control conditions. The river currents were obtained by dividing the cross-sectional area into the discharge volume.

Direct current measurements have been made in four of the cross-sections treated in this report. For comparison with the values obtained by the continuity calculations, average harmonic constituents of the tidal streams in the four sections have also been calculated from the current meter results.

FARQUHARSON (1966) describes a current meter survey in cross-section a_{22} near Pte. des Monts in 1963, and FORRESTER (1967) describes a current meter survey in cross-section a_{21} near Pte. au Père in 1965. Weighted averages were formed from the harmonic constituents of the tidal streams observed at 11 current meter locations in a_{21} and also from those observed at ten current meter locations in a_{22}. The weighting was done on the basis of the distribution of the current meters in the cross-sections, treating the surface and the deeper layers as separate regimes; the same weights were used for each of the harmonic constituents (M_2, etc.).

GODIN (1971) and ANON. (1969a and b) report on current meter surveys in cross-sections a_9 near the Québec Bridge and a_{14} at Ile aux Coudres in 1968. GODIN (personal communication) has provided values for the harmonic constituents of the tidal streams observed at four current meter locations in section a_9 and also for those observed at five current meter locations in section a_{14}. Since the current meters in section a_{14} were fairly evenly distributed throughout the cross-section, equal weight was given to each of the five locations in forming the average harmonic constituents. In section a_9, however, where two meters were located near mid-channel and two near the south shore, only values from the mid-channel locations were used to form the average harmonic constituents.

RESULTS

Table I lists the surface areas of the regions, the areas of their downstream cross-sections, the distance along the channel from Québec to the downstream cross-section, the average river volume discharge, and the corresponding average river current through the cross-section.

Table II a lists the M_2 harmonic constituent of the vertical tide for each region and of the tidal volume transport and mean tidal stream through each downstream cross-section, as calculated from equations (1), (2), and (3). The average M_2 tidal stream through cross-sections a_9, a_{14}, a_{21}, and a_{22} as obtained from the current meters is also shown in Table II a.

TABLE I

No. of Region i	Surface Area, A_i (km²)	Downstream Cross-Section Area, a_i (km²)	Distance from Québec to a_i (km)	River Discharge Volume ($10^6 m^3/s$)	Mean River Current (m/s)
1	347	0.017	− 142	0.0076	0.45
2	14	0.017	− 134	0.0076	0.45
3	27	0.013	− 119	0.0079	0.61
4	48	0.019	− 103	0.0079	0.42
5	31	0.013	− 90	0.0081	0.62
6	24	0.010	− 81	0.0081	0.81
7	24	0.014	− 68	0.0084	0.60
8	52	0.028	− 47	0.0084	0.30
9	96	0.022	− 12	0.0087	0.39
10	110	0.056	+ 25	0.0087	0.16
11	106	0.110	+ 37	0.0087	0.08
12	416	0.200	+ 63	0.0087	0.04
13	392	0.25	+ 81	0.0090	0.04
14	392	0.32	+ 98	0.0090	0.03
15	316	0.57	+ 117	0.0090	0.02
16	683	0.77	+ 154	0.0093	0.012
17	313	0.68	+ 170	0.0093	0.014
18	742	1.04	+ 190	0.0102	0.010
19	769	4.28	+ 220	0.0108	0.003
20	1 278	5.28	+ 258	0.0113	0.002
21	1 501	8.59	+ 290	0.0119	0.001
22	5 804	11.58	+ 402	0.0125	0.001

Tables II b to II g contain the same information for the harmonic constituents S_2, N_2, K_1, O_1, M_4, and MS_4 respectively. All phaselags refer to Eastern Standard Time (EST). Inflowing tidal streams have the positive sign.

It should be noted that the tidal volume transport as a function of distance from Québec varies much more smoothly than does the mean tidal stream. For this reason, interpolation to cross-sections intermediate to those treated in the tables should be done only on the tidal volume transport as a function of distance from Québec: to obtain the corresponding mean tidal stream, the appropriate cross-sectional area should be measured from a chart and divided into the interpolated tidal volume transport.

TABLE II a

Harmonic constituent M_2 (EST)

No. of Region i	Mean Vertical Tide (m)	Tidal Volume Transport ($10^6\ m^3/s$)	Mean Tidal Stream (Calculated) (m/s)	Mean Tidal Stream (Observed) (m/s)
1	(0.03, 085°)	(0.0013, 355°)	(0.08, 355°)	
2	(0.07, 018°)	(0.0014, 350°)	(0.08, 350°)	
3	(0.08, 355°)	(0.0015, 338°)	(0.12, 338°)	
4	(0.26, 326°)	(0.0020, 280°)	(0.11, 280°)	
5	(0.35, 314°)	(0.0032, 257°)	(0.25, 257°)	
6	(0.71, 283°)	(0.0047, 230°)	(0.49, 230°)	
7	(0.86, 275°)	(0.0071, 213°)	(0.52, 213°)	
8	(1.46, 245°)	(0.0156, 178°)	(0.55, 178°)	
9	(1.54, 226°)	(0.0340, 154°)	(1.55, 154°)	(1.67, 153°)
10	(1.83, 174°)	(0.0512, 123°)	(0.91, 123°)	
11	(2.00, 162°)	(0.0739, 104°)	(0.67, 104°)	
12	(1.98, 150°)	(0.1765, 077°)	(0.88, 077°)	
13	(1.93, 137°)	(0.2736, 066°)	(1.10, 066°)	
14	(1.86, 125°)	(0.3655, 058°)	(1.16, 058°)	(1.20, 060°)
15	(1.81, 108°)	(0.4306, 051°)	(0.75, 051°)	
16	(1.68, 092°)	(0.5507, 038°)	(0.71, 038°)	
17	(1.58, 084°)	(0.6028, 033°)	(0.89, 033°)	
18	(1.56, 074°)	(0.7197, 023°)	(0.69, 023°)	
19	(1.45, 062°)	(0.8261, 015°)	(0.19, 015°)	
20	(1.35, 055°)	(0.9994, 004°)	(0.19, 004°)	
21	(1.32, 054°)	(1.226, 356°)	(0.14, 356°)	(0.12, 353°)
22	(1.16, 048°)	(2.056, 339°)	(0.18, 339°)	(0.16, 341°)

TABLE II b
Harmonic constituent S_2 (EST)

No. of Region i	Mean Vertical Tide (m)	Tidal Volume Transport ($10^6\,m^3/s$)	Mean Tidal Stream (Calculated) (m/s)	Mean Tidal Stream (Observed) (m/s)
1	(0.01, 112°)	(0.0005, 022°)	(0.03, 022°)	
2	(0.02, 052°)	(0.0005, 018°)	(0.03, 018°)	
3	(0.02, 027°)	(0.0005, 007°)	(0.04, 007°)	
4	(0.06, 003°)	(0.0007, 324°)	(0.04, 324°)	
5	(0.08, 356°)	(0.0009, 304°)	(0.07, 304°)	
6	(0.14, 329°)	(0.0012, 282°)	(0.12, 282°)	
7	(0.18, 318°)	(0.0017, 264°)	(0.12, 264°)	
8	(0.29, 294°)	(0.0033, 230°)	(0.12, 230°)	
9	(0.34, 278°)	(0.0076, 205°)	(0.35, 205°)	(0.38, 199°)
10	(0.44, 221°)	(0.0117, 169°)	(0.21, 169°)	
11	(0.48, 213°)	(0.0177, 152°)	(0.16, 152°)	
12	(0.49, 197°)	(0.0442, 123°)	(0.22, 123°)	
13	(0.53, 182°)	(0.0715, 111°)	(0.29, 111°)	
14	(0.50, 162°)	(0.0954, 100°)	(0.30, 100°)	(0.29, 102°)
15	(0.48, 142°)	(0.1117, 091°)	(0.20, 091°)	
16	(0.52, 129°)	(0.1486, 076°)	(0.19, 076°)	
17	(0.48, 122°)	(0.1652, 070°)	(0.24, 070°)	
18	(0.50, 113°)	(0.2059, 059°)	(0.20, 059°)	
19	(0.47, 101°)	(0.2437, 050°)	(0.06, 050°)	
20	(0.43, 094°)	(0.3053, 039°)	(0.06, 039°)	
21	(0.42, 095°)	(0.3850, 031°)	(0.04, 031°)	(0.03, 023°)
22	(0.34, 083°)	(0.6368, 015°)	(0.06, 015°)	(0.06, 022°)

TABLE II c

Harmonic constituent N_2 (EST)

No. of Region i	Mean Vertical Tide (m)	Tidal Volume Transport ($10^6\,m^3/s$)	Mean Tidal Stream (Calculated) (m/s)	Mean Tidal Stream (Observed) (m/s)
1	(0.01, 045°)	(0.0003, 315°)	(0.02, 315°)	
2	(0.01, 353°)	(0.0003, 312°)	(0.02, 312°)	
3	(0.02, 328°)	(0.0003, 302°)	(0.02, 302°)	
4	(0.04, 309°)	(0.0005, 264°)	(0.03, 264°)	
5	(0.06, 307°)	(0.0006, 248°)	(0.05, 248°)	
6	(0.10, 266°)	(0.0008, 226°)	(0.08, 226°)	
7	(0.12, 246°)	(0.0010, 205°)	(0.07, 205°)	
8	(0.19, 225°)	(0.0019, 164°)	(0.07, 164°)	
9	(0.33, 188°)	(0.0055, 117°)	(0.25, 117°)	(0.30, 140°)
10	(0.28, 155°)	(0.0088, 094°)	(0.16, 094°)	
11	(0.30, 142°)	(0.0124, 081°)	(0.11, 081°)	
12	(0.36, 125°)	(0.0308, 052°)	(0.15, 052°)	
13	(0.37, 114°)	(0.0497, 041°)	(0.20, 041°)	
14	(0.33, 099°)	(0.0654, 033°)	(0.21, 033°)	(0.21, 031°)
15	(0.35, 082°)	(0.0776, 025°)	(0.14, 025°)	
16	(0.30, 064°)	(0.0977, 012°)	(0.13, 012°)	
17	(0.31, 056°)	(0.1073, 007°)	(0.16, 007°)	
18	(0.31, 049°)	(0.1309, 357°)	(0.13, 357°)	
19	(0.30, 038°)	(0.1535, 348°)	(0.04, 348°)	
20	(0.27, 031°)	(0.1887, 337°)	(0.04, 337°)	
21	(0.25, 031°)	(0.2323, 330°)	(0.03, 330°)	(0.03, 330°)
22	(0.24, 030°)	(0.4129, 316°)	(0.04, 316°)	(0.04, 318°)

TABLE II d

Harmonic constituent K_1 (EST)

No. of Region *i*	Mean Vertical Tide (m)	Tidal Volume Transport ($10^6\, m^3/s$)	Mean Tidal Stream (Calculated) (m/s)	Mean Tidal Stream (Observed) (m/s)
1	(0.02, 090°)	(0.0004, 000°)	(0.02, 000°)	
2	(0.02, 052°)	(0.0004, 358°)	(0.02, 358°)	
3	(0.03, 034°)	(0.0004, 352°)	(0.03, 352°)	
4	(0.06, 359°)	(0.0005, 327°)	(0.03, 327°)	
5	(0.08, 353°)	(0.0006, 311°)	(0.05, 311°)	
6	(0.12, 330°)	(0.0007, 294°)	(0.07, 294°)	
7	(0.14, 329°)	(0.0009, 281°)	(0.07, 281°)	
8	(0.19, 302°)	(0.0013, 251°)	(0.05, 251°)	
9	(0.19, 288°)	(0,0024, 224°)	(0.11, 224°)	(0.12, 227°)
10	(0.23, 263°)	(0.0038, 202°)	(0.07, 202°)	
11	(0.24, 253°)	(0.0054, 189°)	(0.05, 189°)	
12	(0.24, 246°)	(0.0121, 170°)	(0.06, 170°)	
13	(0.23, 240°)	(0.0185, 163°)	(0.07, 163°)	
14	(0.25, 232°)	(0.0254, 157°)	(0.08, 157°)	(0.07, 206°)
15	(0.25, 222°)	(0.0308, 153°)	(0.05, 153°)	
16	(0.24, 215°)	(0.0419, 145°)	(0.05, 145°)	
17	(0.24, 213°)	(0.0471, 142°)	(0.07, 142°)	
18	(0.25, 209°)	(0.0596, 137°)	(0.06, 137°)	
19	(0.24, 205°)	(0.0721, 133°)	(0.017, 133°)	
20	(0.23, 200°)	(0.0919, 128°)	(0.017, 128°)	
21	(0.23, 201°)	(0.1157, 124°)	(0.014, 124°)	(0.013, 150°)
22	(0.23, 201°)	(0.2111, 118°)	(0.018, 118°)	(0.015, 120°)

TABLE II e

Harmonic constituent O_1 (EST)

No. of Region i	Mean Vertical Tide (m)	Tidal Volume Transport ($10^6 m^3/s$)	Mean Tidal Stream (Calculated) (m/s)	Mean Tidal Stream (Observed) (m/s)
1	(0.02, 052°)	(0.0004, 322°)	(0.02, 322°)	
2	(0.03, 020°)	(0.0004, 320°)	(0.02, 320°)	
3	(0.03, 005°)	(0.0005, 316°)	(0.04, 316°)	
4	(0.07, 336°)	(0.0006, 296°)	(0.03, 296°)	
5	(0.09, 330°)	(0.0007, 284°)	(0.05, 284°)	
6	(0.13, 312°)	(0.0008, 271°)	(0.08, 271°)	
7	(0.14, 306°)	(0.0010, 260°)	(0.07, 260°)	
8	(0.18, 286°)	(0.0014, 236°)	(0.05, 236°)	
9	(0.20, 271°)	(0.0024, 209°)	(0.11, 209°)	(0.13, 196°)
10	(0.22, 244°)	(0.0036, 187°)	(0.06, 187°)	
11	(0.24, 235°)	(0.0050, 174°)	(0.05, 174°)	
12	(0.24, 232°)	(0.0113, 156°)	(0.06, 156°)	
13	(0.24, 221°)	(0.0172, 147°)	(0.07, 147°)	
14	(0.25, 214°)	(0.0234, 141°)	(0.07, 141°)	(0.06, 183°)
15	(0.24, 204°)	(0.0281, 136°)	(0.05, 136°)	
16	(0.24, 197°)	(0.0381, 128°)	(0.05, 128°)	
17	(0.23, 195°)	(0.0427, 125°)	(0.06, 125°)	
18	(0.24, 192°)	(0.0541, 120°)	(0.05, 120°)	
19	(0.23, 187°)	(0.0651, 116°)	(0.015, 116°)	
20	(0.22, 182°)	(0.0829, 111°)	(0.016, 111°)	
21	(0.23, 183°)	(0.1047, 107°)	(0.012, 107°)	(0.010, 107°)
22	(0.21, 183°)	(0.1858, 101°)	(0.016, 101°)	(0.015, 115°)

TABLE II f

Harmonic constituent M_4 (EST)

No. of Region i	Mean Vertical Tide (m)	Tidal Volume Transport ($10^6 m^3/s$)	Mean Tidal Stream (Calculated) (m/s)	Mean Tidal Stream (Observed) (m/s)
1	(0.01, 039°)	(0.0006, 309°)	(0.04, 309°)	
2	(0.02, 301°)	(0.0006, 301°)	(0.04, 301°)	
3	(0.03, 254°)	(0.0004, 277°)	(0.03, 277°)	
4	(0.09, 217°)	(0.0008, 142°)	(0.04, 142°)	
5	(0.10, 196°)	(0.0016, 124°)	(0.12, 124°)	
6	(0.21, 124°)	(0.0022, 083°)	(0.23, 083°)	
7	(0.24, 113°)	(0.0033, 057°)	(0.24, 057°)	
8	(0.33, 043°)	(0.0051, 352°)	(0.18, 352°)	
9	(0.22, 009°)	(0.0089, 312°)	(0.40, 312°)	(0.34, 318°)
10	(0.27, 273°)	(0.0073, 253°)	(0.13, 253°)	
11	(0.27, 256°)	(0.0113, 207°)	(0.10, 207°)	
12	(0.15, 239°)	(0.0256, 171°)	(0.13, 171°)	
13	(0.05, 173°)	(0.0264, 159°)	(0.11, 159°)	
14	(0.05, 068°)	(0.0207, 159°)	(0.07, 159°)	(0.04, 146°)
15	(0.09, 046°)	(0.0138, 172°)	(0.02, 172°)	
16	(0.08, 060°)	(0.0060, 269°)	(0.008, 269°)	
17	(0.06, 077°)	(0.0087, 304°)	(0.013, 304°)	
18	(0.05, 123°)	(0.0135, 353°)	(0.013, 353°)	
19	(0.03, 113°)	(0.0195, 003°)	(0.005, 003°)	
20	(0.03, 064°)	(0.0285, 353°)	(0.005, 353°)	
21	(0.03, 085°)	(0.0401, 354°)	(0.005, 354°)	(0.007, 021°)
22	(0.01, 081°)	(0.0550, 353°)	(0.005, 353°)	(0.008, 332°)

TABLE II g

Harmonic constituent MS_4 (EST)

No. of Region i	Mean Vertical Tide (m)	Tidal Volume Transport ($10^6 m^3/s$)	Mean Tidal Stream (Calculated) (m/s)	Mean Tidal Stream (Observed) (m/s)
1	(0.003, 072°)	(0.0003, 342°)	(0.02, 342°)	
2	(0.01, 000°)	(0.0003, 336°)	(0.02, 336°)	
3	(0.02, 300°)	(0.0003, 314°)	(0.02, 314°)	
4	(0.04, 268°)	(0.0004, 205°)	(0.02, 205°)	
5	(0.04, 251°)	(0.0007, 184°)	(0.05, 184°)	
6	(0.07, 182°)	(0.0009, 148°)	(0.09, 148°)	
7	(0.09, 160°)	(0.0012, 116°)	(0.09, 116°)	
8	(0.12, 105°)	(0.0019, 052°)	(0.07, 152°)	
9	(0.11, 073°)	(0.0042, 008°)	(0.19, 008°)	(0.22, 349°)
10	(0.13, 324°)	(0.0033, 301°)	(0.06, 301°)	
11	(0.13, 318°)	(0.0059, 260°)	(0.05, 260°)	
12	(0.07, 295°)	(0.0127, 227°)	(0.06, 227°)	
13	(0.03, 237°)	(0.0139, 212°)	(0.06, 212°)	
14	(0.02, 109°)	(0.0115, 214°)	(0.04, 214°)	(0.04, 229°)
15	(0.04, 086°)	(0.0088, 230°)	(0.02, 230°)	
16	(0.04, 100°)	(0.0057, 284°)	(0.007, 284°)	
17	(0.02, 120°)	(0.0055, 303°)	(0.008, 303°)	
18	(0.02, 187°)	(0.0027, 344°)	(0.003, 344°)	
19	(0.02, 186°)	(0.0034, 049°)	(0.001, 049°)	
20	(0.01, 137°)	(0.0056, 048°)	(0.001, 048°)	
21	(0.01, 162°)	(0.0094, 058°)	(0.001, 058°)	(0.003, 079°)
22	(0.003, 251°)	(0.0096, 089°)	(0.001, 089°)	(0.001, 005°)

DISCUSSION

Comparison in Tables II a to II g of the average tidal streams in cross-sections a_{21} and a_{22} obtained by the continuity calculation and by direct current measurement shows remarkably good agreement: the greatest disagreement is 0.02 m/s, which occurs for the M_2 constituent. This agreement is evidence of the accuracy both of the continuity calculations and of the overall performance and calibration of the current meters in the range of speeds encountered. The meters employed in section a_{22} were Hydrowerkstatten paddlewheel and propeller type, and Neyrpic-BBT propeller type. Those employed in section a_{21} were Braincon meters with Savonius rotors.

The agreement in sections a_9 and a_{14} between tidal streams calculated by continuity and measured by current meters is also very good, but not as good as that in sections a_{21} and a_{22}. The poorer agreement in the upstream sections may be due partly to more erratic behaviour of the current meters in the higher-speed currents and partly to the greater effect of sloping banks in the narrower cross-sections, for which no allowance was made in the continuity calculations. The current meters employed in section a_{14} were Ott-Hydrowerkstatten and Plessey propeller types, and those in section a_9 were Ott-Hydrowerkstatten only. The meters in all four sections were moored self-recording instruments, and the constituents of the tidal streams were estimated from their records by harmonic analysis (FARQUHARSON, 1966; FORRESTER, 1967; and GODIN, 1971).

The current or tidal stream calculated by continuity for a particular cross-section is the average over the entire cross-section, and so tells nothing of possible variations from top to bottom or from shore to shore; direct current measurement is still required to supply this information. The continuity values are, however, believed to be more accurate estimates of the average flows than could be obtained by direct current measurement with the limited quantity and reliability of equipment at present available.

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