Geophys. J. R. astr. Soc. (1968) 15, 517–528.

The Flow of Water through the Menai Straits

J. G. Harvey

(Received 1967 November 28)

Summary

Observations of the flow of water through the Menai Straits by various methods have all indicated a residual transport of water towards the south-west during a semi-diurnal tidal period. Estimates of the magnitude of this transport indicate that it is of the order of 30 million m^3 during one semi-diurnal tidal period, corresponding to an average residual velocity of approximately 15 cm/s to the south-west. Possible causes of this residual flow are considered, and it is shown that the computed tidal flow in a short channel connecting two basins with the same mean water level but different tidal ranges and phases and in which the tidal heights follow precise sine curves may exhibit similar features, when a friction term is included in the equation of motion, to those observed in the Menai Straits.

Introduction

The Menai Straits, which separate the island of Anglesey from the mainland of Britain, occupy a composite valley which was submerged in the Post-Glacial (Embleton 1964). That part of the Menai Straits which extends from Bangor to Belan (Fig. 1) comprises a channel some 20 km long, mean width about 800 m, but narrowing to about 300 m at either end of the Swellies. The maximum sounding below chart datum is 22 m just to the south-west of the Swellies; the shallowest sections across the Straits are to be found between Belan and Caernarvon and between Caernarvon and Portdinorwic, where the sill depths are between 1 and 2 m below chart datum and the floor covered by sand; the minimum cross sectional area at most states of the tide is, however, found within, or close to, the Swellies where the Straits are narrowest and where the bottom is mainly rocky and extremely irregular (Admiralty Chart 1464, 1963). The mean spring and neap tidal ranges at Menai Bridge are 6·6 m and 3·4 m respectively and at Belan 4·1 m and 1·8 m respectively (Admiralty Tide Tables, Vol. I). The tidal ranges are therefore of similar magnitude to the mean depths.

Preliminary observations of the flow of water through the Menai Straits were made by Dr C. P. Spencer during 1956 (personal communication). On 1956 May 15, the mean velocities of floats with vanes suspended at depths of 1 m, 5·5 m and 9 m were measured over a distance of 275 m in the vicinity of position D (Fig. 1) during a period of 10 h. The mean maximum velocity of the three floats at any time during the north-easterly tidal flow was about 80 cm/s, that during the south-westerly tidal flow 150 cm/s. On 1956 November 3, a float with a vane 1 m below the surface was released at position G (Fig. 1) at the start of the south-westerly tidal flow and followed during a complete semi-diurnal tidal period. At the end of the south-westerly tidal flow it had reached position A and during the north-easterly tidal flow moved from

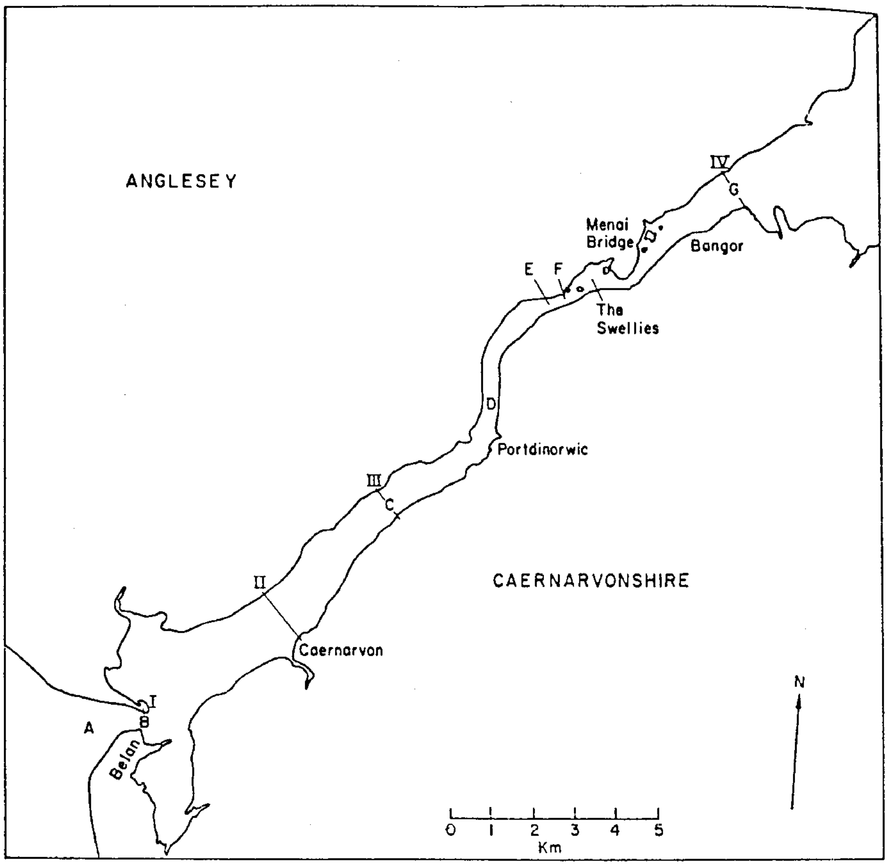

FIG. 1. The Menai Straits showing positions and sections referred to in the text.

position A to position F. Its net movement was therefore 4·8 km in 12·5 h, corresponding to a mean velocity of about 11 cm/s towards the south-west. The tidal range on the earlier occasion was just above average and the wind was south-westerly, Beaufort force 2-4. On the later occasion the tidal range was almost exactly the mean spring tidal range and the wind was mainly northerly, Beaufort force 0–3.

On 1961 April 17–18, a recording current meter was moored 1·2 m above the bottom at position E (Fig. 1) for a 25 h period by British Insulated Callenders Construction Co. Ltd. on behalf of the Central Electricity Generating Board (to whom I am indebted for access to the data). The maximum velocity recorded to the south-west during this period was 120 cm/s, that to the north-east 80 cm/s. During this period spring tidal ranges were experienced and the wind was light northerly.

All of these observations have indicated that the south-westerly flowing tidal current is typically stronger than that flowing to the north-east. Biological investigations have also indicated the possibility of a small residual flow of water from Liverpool Bay into Caernarvon Bay through the Menai Straits (e.g. Jones & Haq 1963). The purpose of this investigation was to confirm this residual flow, to estimate its magnitude, and to determine its cause with a view to predicting variations in it. The flow was examined by the use of Woodhead sea-bed drifters (Lee *et al.* 1965), current measurements from anchored vessels, and salinity observations. Tide gauges were installed at four positions along the Menai Straits to examine the cause of the flow.

Observations of the flow

(a) *Woodhead sea-bed drifters.* Woodhead sea-bed drifters were released at positions B, C and G (Fig. 1). The total number of drifters to be released at each position on each occasion was divided into 12 equal batches, and the batches released at hourly intervals to obtain an even distribution throughout a semi-diurnal tidal period. From Fig. 2 it can be seen that their predominant movement within the Menai Straits was to the south-west. The differences between the rate of movement of those released at position G in September 1962 and those released in the same position in June 1963 may be due to the earlier release having been made during a period of spring tides and the latter during a period of neap tides, or it may have resulted from a difference in the method of release of the drifters—in September 1962 the drifters were released at the sea surface to sink slowly to the bottom, whereas in June 1963 they were attached to a weight so that they sank immediately and were released on the bottom when a soluble material dissolved. The mean velocity of the fastest moving drifters from station G within the Menai Straits was found to be approximately 5 cm/s towards the south-west, but the velocity shown by drifters is usually less than the velocity of the near bottom water as the drifters which are found

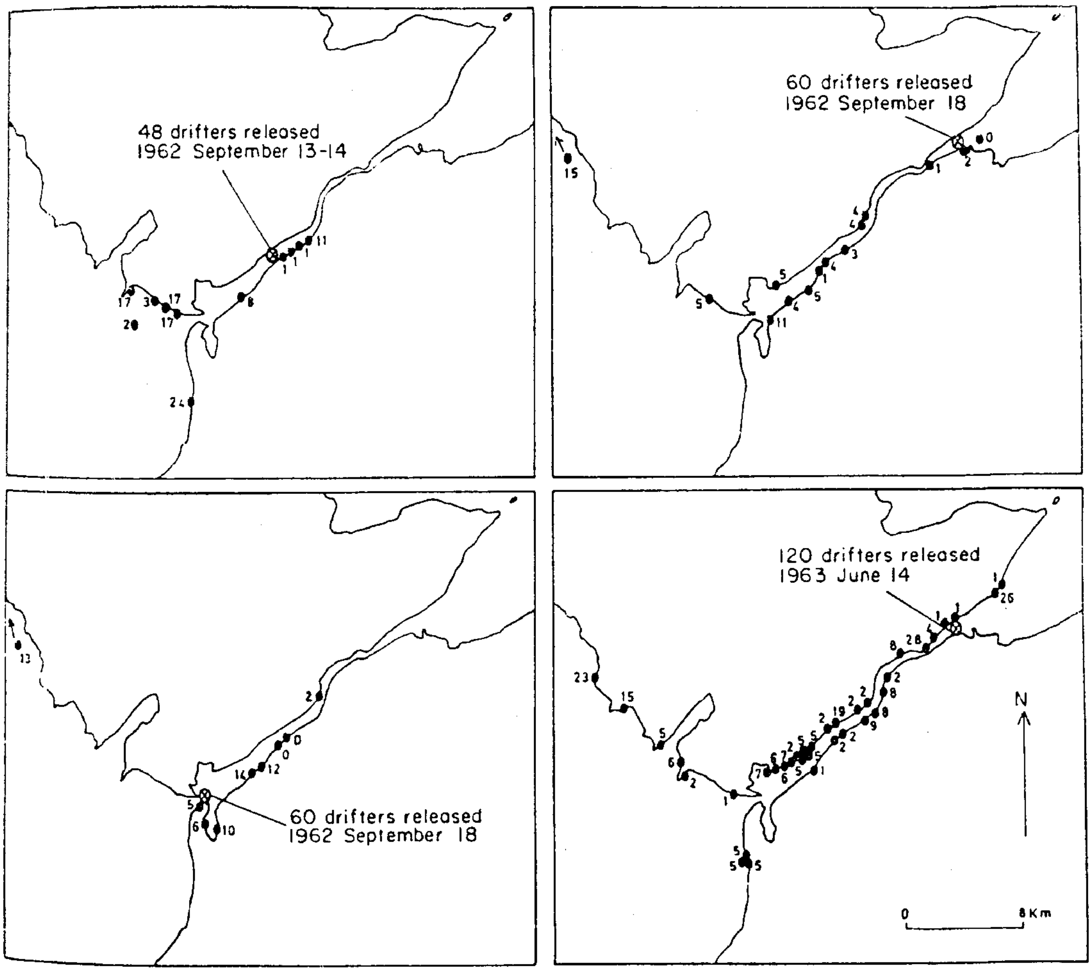

FIG. 2. Recoveries of sea-bed drifters within 28 days of release in the Menai Straits; the numbers indicate the time interval, in days, between the release and recovery of each drifter.

may have become entangled with obstacles or may have lain on the beaches for some time before being found, and it may be expected that the water near the surface and at mid-depths will move faster than that close to the bottom.

(b) *Direct current measurements.* Admiralty 18 ft drift poles were used in cross sections I and II (Fig. 1) to obtain the mean velocity in the upper 5 m of water, and direct reading current meters were used from anchored vessels in cross sections III and IV to obtain velocity profiles from the surface to the bottom from which the mean velocity in the water column was determined. In each case observations were made throughout at least one semi-diurnal tidal period. The topography of these cross sections and the positions along them at which observations were made are shown in Fig. 3. In Fig. 4 are shown the components of the observed mean velocities across the sections together with the tidal heights. The rate of transport of water across each section was then calculated as the product of the mean velocity from the surface to 5 m or bottom at each position of observation and the cross sectional area (taking account of tidal variations) (Fig. 5). This is likely to lead to an overestimation of the rate of transport, particularly in sections I and II where the mean velocity used was that between the surface and 5 m. The rate of transport as calculated from each observation position was then integrated over the periods of the south-westerly and north-easterly flowing tides (Table 1). It will be seen that the residual flow during a complete semi-diurnal tidal period was towards the south-west in every case, and varied between 9 and 38 million m^3, the mean value being 28 million m^3. In addition to apparent variations associated with inadequacies in the data used, variations may also exist between one position and another associated with the inflow of fresh water (though for average conditions the total inflow of fresh water into the Menai Straits has been estimated as less than 0·5 million m^3 during a semi-diurnal tidal period), and between one occasion and another associated with changes in wind conditions, tidal conditions or with the general circulation of the adjacent parts of the Irish Sea. The degree of consistency found, however, would appear to indicate a reasonably continuous south-westerly flow (though none of the observations were made during periods when the wind exceeded Beaufort force 4) and perhaps provides some

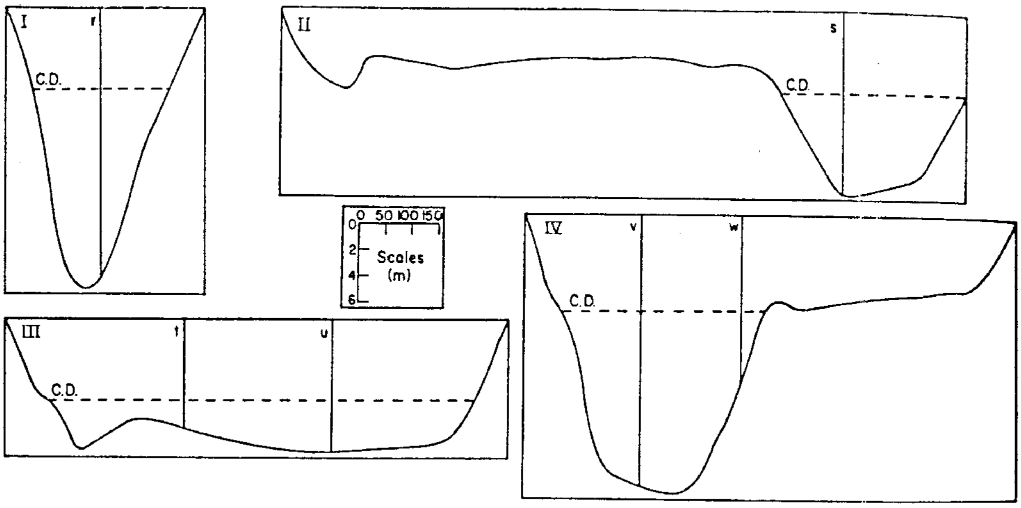

FIG. 3. Sections across the Menai Straits and positions where current measurements were made. See Fig. 1 for location of sections. (C.D.: chart datum).

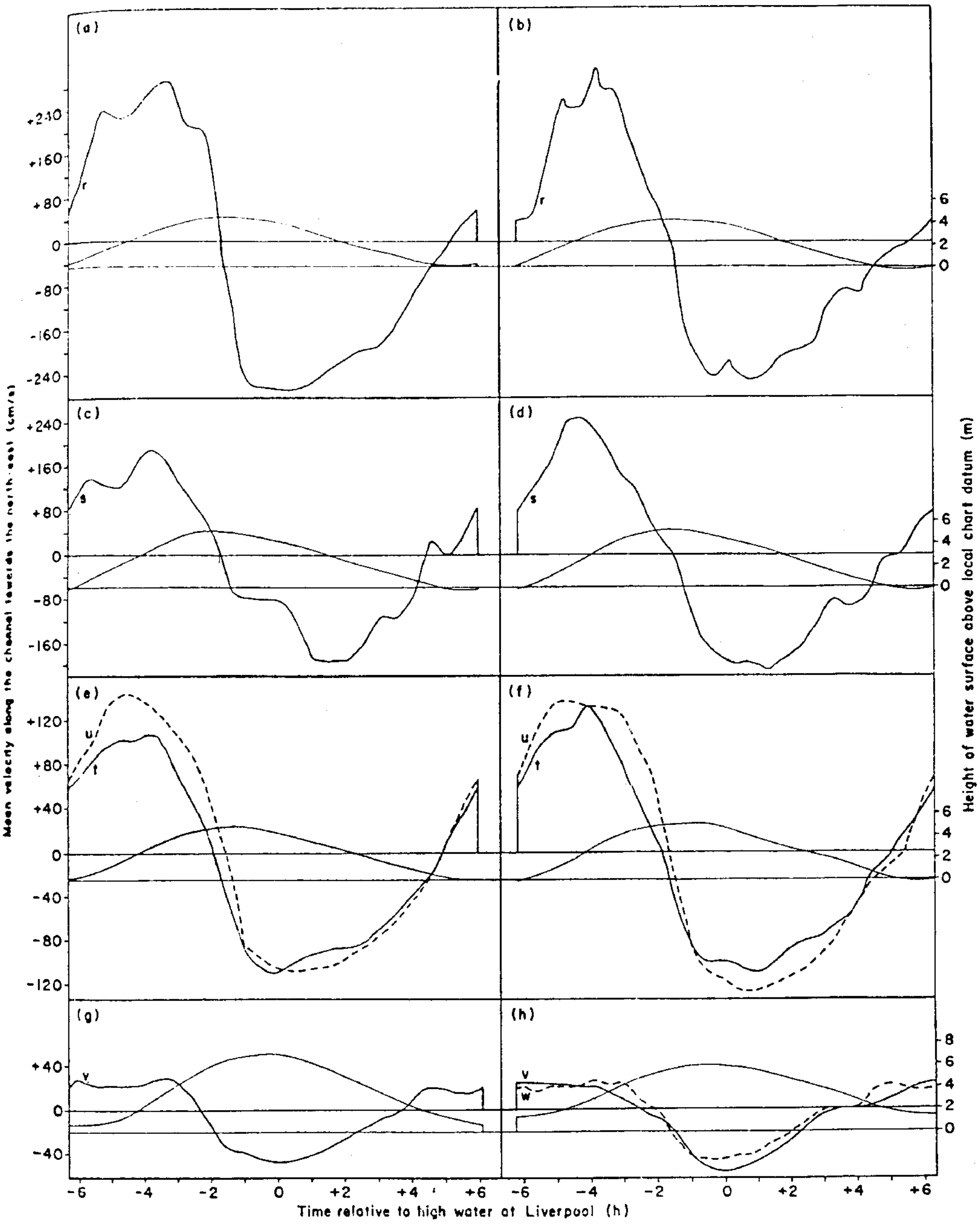

FIG. 4. Components of observed mean velocities along the Menai Straits and corresponding tidal heights.

(a) Section I; 1130–2400 h, 1962 October 12; wind N.E. force 1–2; mean tidal range (Liverpool) 8·9 m.
(b) Section I; 0000–1230 h, 1962 October 13; wind N.E. force 0–1; mean tidal range (Liverpool) 9·3 m.
(c) Section II; 1000–2230 h, 1962 September 15; wind W–N.W. force 2–3; mean tidal range (Liverpool) 9·7 m.
(d) Section II; 2300–1130 h, 1962 September 15–16; wind W. force 3–4; mean tidal range (Liverpool) 9·9 m.
(e) Section III; 1030–2300 h, 1962 September 13; wind variable force 0–1; mean tidal range (Liverpool) 8·5 m.
(f) Section III; 2300–1130 h, 1962 September 13–14; wind S.–S.E. force 1–4; mean tidal range (Liverpool) 9·2 m.
(g) Section IV; 0700–1900 h, 1962 September 18; wind N.W. force 2–4; mean tidal range (Liverpool) 8·9 m.
(h) Section IV; 0700–1930 h, 1963 June 14; wind N.–N.W. force 2–3; mean tidal range (Liverpool) 5·8 m.

See Fig. 1 and Fig. 3 for locations of observations. Mean neap tidal range (Liverpool) 4·6 m; mean spring tidal range (Liverpool) 8·4 m.

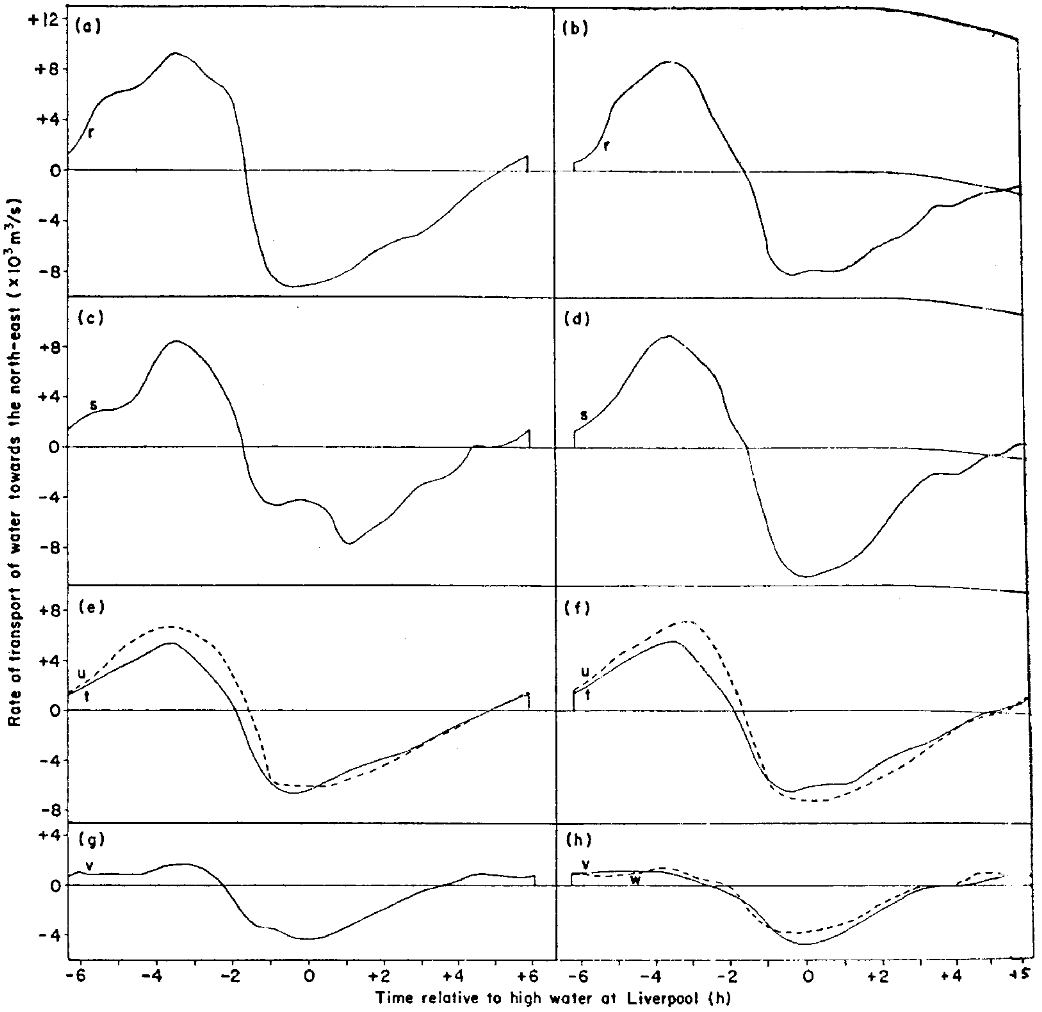

FIG. 5. Transport of water along the Menai Straits computed from observed velocities. Locations and occasions of observations are as in Fig. 4.

justification for the methods used. In particular it will be noted that there is no significant difference between the mean value of the residual flow across sections I and II, where the mean velocity in the upper 5 m only was used, and that across sections III and IV, where the mean velocity used was that between surface and bottom.

It will also be seen from Fig. 4 that during most of the period when the water level is rising in the Menai Straits the water is flowing towards the north-east and that during most of the period when the water level is falling the water is flowing towards the south-west. Hence the greatest tidal transport of water takes place across section I and the tidal transport decreases north-eastwards so that across section IV it is only about one-fifth that across section I and the residual transport exceeded the tidal transport on the occasions when observations were made here (Table 1). It will also be seen, however, that at section IV the flow of water reverses in direction some 1·5 to 2 h before high water and 2 to 2·5 h before low water. The designation of the tidal streams as the ebb stream and the flood stream is therefore inappropriate at the north-eastern end of the Menai Straits.

Table 1

Transport of water through sections across the Menai Straits during semi-diurnal tidal periods (millions m³)

Section (see Fig. 1)	Occasion: (see Fig. 4)	Position of current measurement (see Fig. 3)	Towards N.E.	Towards S.W.	Residual (towards S.W.)
I	(a)	(r)	109	138	29
I	(b)	(r)	87	119	32
II	(c)	(s)	83	96	13
II	(d)	(s)	91	129	38
III	(e)	(t)	56	90	34
III	(e)	(u)	80	89	9
III	(f)	(t)	60	94	34
III	(f)	(u)	80	107	27
IV	(g)	(v)	21	55	34
IV	(h)	(v)	16	51	35
IV	(h)	(w)	20	43	23

(c) *Salinity observations.* Observations of salinity were made throughout a semi-diurnal tidal period at positions B and G (Fig. 6(a)). Although the bottom observations at position B are incomplete it is clear that the range of salinity is very appreciably greater at position B than at position G. Further observations of surface salinity at position B and at Menai Bridge Pier during another semi-diurnal tidal period show a similar difference (Fig. 6(b)). These differences may be taken to indicate that whereas the water flowing past position G has all followed a similar course from Liverpool Bay, that flowing past position B had come from at least two different sources, viz. from Caernarvon Bay where the water is of relatively high salinity, and from Liverpool Bay after passing through the Menai Straits and being appreciably diluted. The temperature ranges would not be expected to show a similar difference

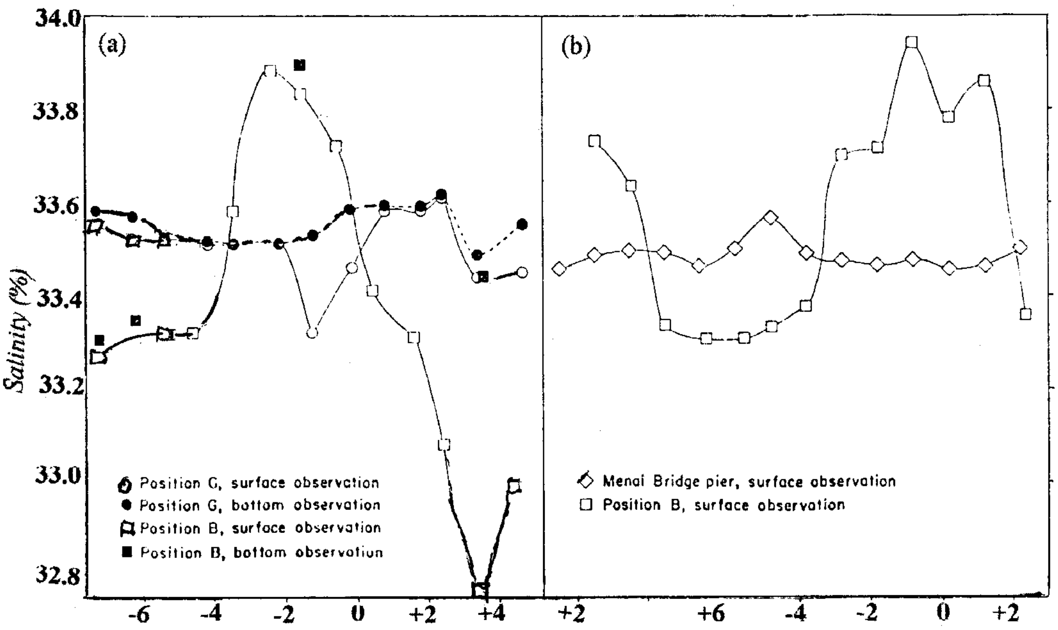

FIG. 6. Variation of salinity during semi-diurnal tidal periods. (a) 0700–2000 h, 1962 September 18. (b) 1100-0100 h, 1962 October 12–13.

as the temperature of the water entering the Menai Straits at the north-eastern end may be considerably modified if the water passes over the Lavan Sands which are uncovered at low water.

Discussion

All of the evidence described indicates a south-westerly residual flow of water through the Menai Straits. The volume of water within the length of the Menai Straits under consideration at mean tidal level is very approximately 80 million m^3. If the residual flow is 28 million $m^3/12\frac{1}{2}$ h to the south-west, water initially at position G (Fig. 1) will be at position B approximately three semi-diurnal tidal periods later, corresponding to an average velocity of approximately 15 cm/s. This compares with the velocity of 5 cm/s indicated by the sea-bed drifters which it has already been indicated is likely to be appreciably less than the residual velocity of the main mass of water, and 11 cm/s shown by Dr Spencer's observations on 1956 November 3.

The following possible causes of a residual flow of water through the Menai Straits were considered:

1. Wind stress on the water surface in the Menai Straits.
2. Piling up of water at one end of the Menai Straits due to wind stress on the water surface in the adjacent parts of the Irish Sea.
3. The general circulation pattern in the adjacent parts of the Irish Sea.
4. A higher mean water level at one end of the Menai Straits than at the other end associated with some cause other than 2 or 3 above.
5. Dynamical effects on the tidal flow within the Menai Straits.

Observations of the residual flow during periods of light winds from various directions would appear to rule out the first possible cause. Recording tide gauges were installed at Menai Bridge, Portdinorwic, Caernarvon, and Belan in order to investigate the remaining possibilities. The mean water levels at these gauges have been analysed elsewhere (Harvey 1967), and show that during a 35 day period there was no significant difference between the mean water level at the two ends of the Menai Straits. On occasions when the residual flow was observed between 1962 September 13 and 18, the mean 25 h water levels at Menai Bridge were consistently less than those at Caernarvon, though generally by an amount less than the estimated accuracy of the mean levels. This would appear to rule out the possible causes 2, 3 and 4 as being responsible for the observed residual flow, although they could lead to variations in the magnitude of the residual flow. The significant correlation coefficient found between the mean southerly wind component and the difference between mean water levels at Caernarvon and Menai Bridge 24 h later (25 h mean values) indicates that variations in the southerly wind component are likely to bring about variations in the residual flow.

Of particular significance from the tide gauge records is the observation that the mean water level at Portdinorwic is significantly higher than that at either end of the Menai Straits. This appears to be attributable to frictional effects on the tidal flow in the Swellies and indicates the importance of the fifth possible cause listed in producing the residual flow.

Attention has already been drawn to the discrepancy between times of high and low water and slack waters at the north-eastern end of the Menai Straits. This discrepancy exists also in the Swellies, though to a lesser extent than at position G. It may be estimated that the differences in time between slack water and the following high or low water in the Swellies is normally about one hour. It appears that the flow of water through the Menai Straits is controlled essentially by the conditions in the Swellies as the frictional stress on the tidal current is greatest here. This is shown by profiles of the water surface along the Menai Straits which indicate a marked step in the profile between Menai Bridge and Portdinorwic at most states of the tide.

As a result of the discrepancies between times of slack waters and high and low waters in the Swellies the mean water level during the period of the south-westerly tidal flow is significantly higher than that during the north-easterly tidal flow. This affects the transport of water in two ways. When the water level is higher the frictional stress per unit mass of water in the Swellies is less and hence for the same horizontal pressure gradient the mean velocity in any cross section will be greater. Secondly, the higher mean water level is associated with a greater volume of water present to move. It therefore seems that the residual transport of water to the south-west during a semi-diurnal tidal period may be attributed to this discrepancy.

The higher mean water level at Portdinorwic than at either end of the Menai Straits may also be attributed to the greater frictional stress on the north-easterly tidal flow through the Swellies in comparison with that during the south-westerly tidal flow. The greater frictional stress on the north-easterly flow will lead to the piling up of water at Portdinorwic, which will not be balanced by a corresponding lowering of the water level during the south-westerly flow as the mean frictional stress on the water in the Swellies will then be less.

In order to obtain a better understanding of the flow of the water through the Swellies the equation of motion has been examined in a short channel of rectangular cross section with the floor forming a level surface, and which connects two large basins with the same mean water level and in which the tidal heights follow precise sine curves. Three terms were considered to be of major importance, viz. a horizontal pressure gradient term resulting from the difference in water level between the two ends of the channel, a friction term resulting from friction between the moving water and the floor of the channel, and an acceleration term. Thus

$$\frac{\partial u}{\partial t}+\frac{ku|u|}{\bar{H}}=\frac{g(h_A-h_B)}{x}, \tag{1}$$

(see e.g. Proudman 1953, Chap. 14),

where u is the depth mean velocity half way along the channel,

t the time,

k the coefficient of friction,

$\bar{H}$ the depth mid-way along the channel $=\dfrac{h_A+h_B}{2}$,

g the acceleration due to gravity,

h_A the depth of water at end A of the channel,

h_B the depth of water at end B of the channel, and

x the length of the channel.

h_A and h_B are defined by:

$h_A = a+A_A \sin pt$,

$h_B = a+A_B \sin(pt+\varepsilon)$,

where a is the mean depth of the channel,

A_A the amplitude of the tidal range at end A,

A_B the amplitude of the tidal range at end B,

p the semi-diurnal tidal period, and

ε the phase lag of the tide at B behind that at A.

Equation (1) was solved numerically for u during complete semi-diurnal tidal periods by computer using the Runge–Kutta method with particular values of

k, a, p, g, x and ε and various values of A_A and A_B. Values were selected to represent, very approximately, the section of the Menai Straits between Menai Bridge (end A) and Portdinorwic (end B) for neap, mean and spring tidal conditions. The following values were used:

$k = 0{\cdot}005$,
$a = 5\,\text{m}$,
$p = 0{\cdot}505\,\text{rad/h}$,
$g = 981\,\text{cm/s}^2$,
$x = 6{\cdot}5\,\text{km}$,
$\varepsilon = 0{\cdot}40\,\text{rad}$.

	Neap tide	Mean tide	Spring tide
A_A(m)	1·71	2·50	3·29
A_B(m)	1·22	1·83	2·45

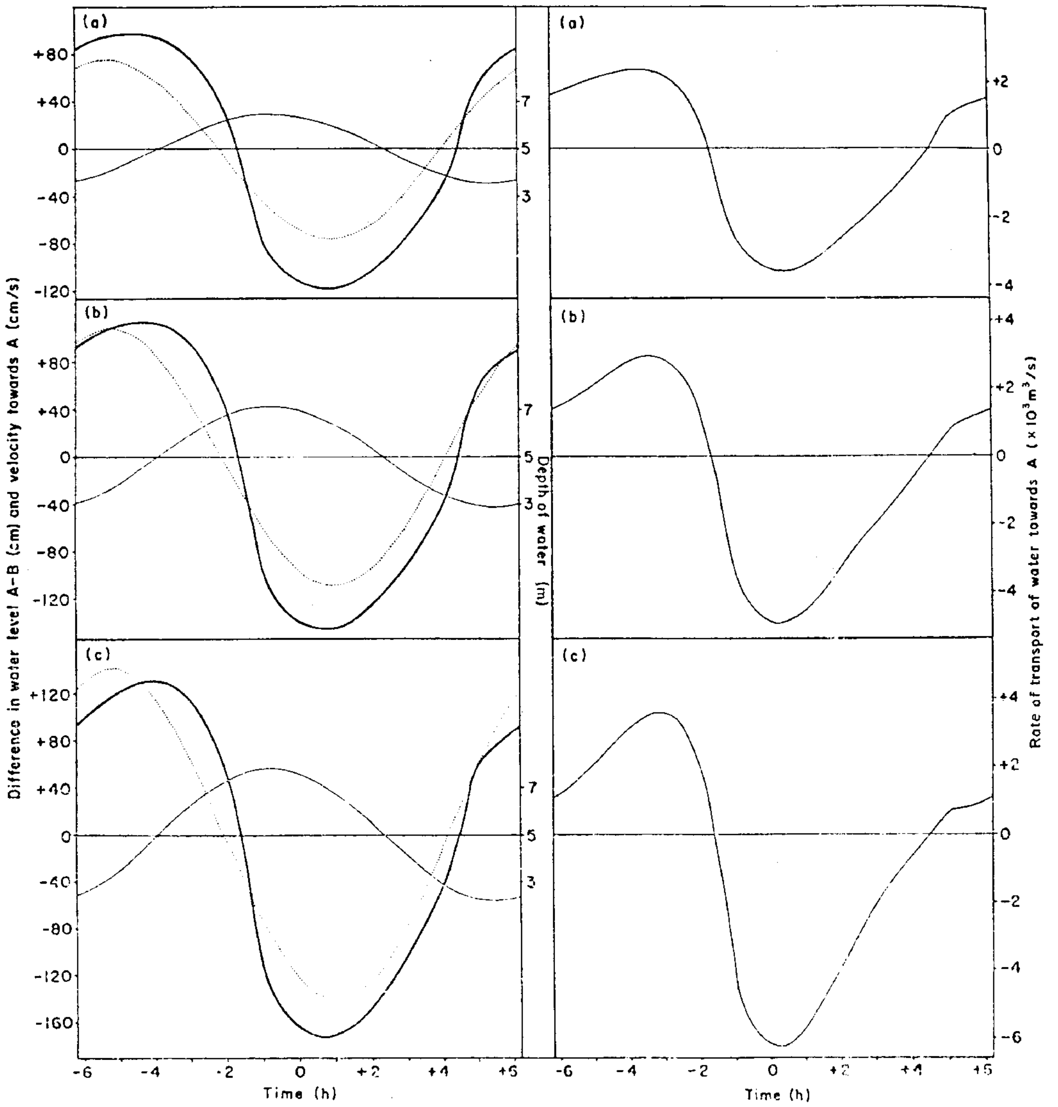

FIG. 7(i). Computed difference in water level between two ends of a channel (dotted line), and velocity (thick line) and depth (thin line) of water at a position mid-way along the channel.

FIG. 7(ii). Computed transport of water at a position mid-way along the channel. (a) Neap tide conditions, (b) mean tide conditions, (c) spring tide conditions.

Initial values were selected having regard to the observations made in cross sections III and IV and the computations were continued for at least 12·5 h before the output was accepted to overcome errors in the initial values used. A time interval of 15 min between successive computations was usually found to be satisfactory, but in the case of spring tidal data it was found necessary to reduce this to avoid instability in the numerical work, and a time interval of 6 min was used.

The results obtained (Fig. 7(i)) reproduce the main features of the observed flow in the Swellies, namely higher velocities towards the south-west than towards the north-east and intervals of approximately 55 min between each slack water and the following low water or high water. In each case the phase lag of the flow behind the horizontal pressure gradient term is some 25 min due to the inertia of the flow. Assuming that the cross section of the channel is rectangular, and its width 500 m, the volume transport of the water through the channel has been calculated for the neap, mean and spring tidal conditions (Fig. 7(ii)). Again the main features of the observed flow are reproduced. The residual transports of water through the channel during semi-diurnal tidal periods are all to the south-west, and were found to be 13 million m^3 for neap tides, 24 million m^3 for mean tidal conditions and 35 million m^3 for spring tides, providing an indication of the possible effect of tidal range on the residual flow of water through the Menai Straits.

The equation of motion was also solved numerically for two hypothetical cases. The same values of k, a, p, g and x were employed as above. In the first hypothetical case (Y) the phase difference between the tide at end A and that at end B(ε) was reduced to zero and values of 2·28 m and 1·68 m were used for A_A and A_B respectively, and in the second hypothetical case (Z) both A_A and A_B were made equal to 1·98 m and ε was taken as 0·40 rad. In case Y (Fig. 8(a)) the residual transport of water during a semi-diurnal tidal period was found to be 34 million m^3 towards the south-west; in case Z (Fig. 8(b)) it was found to be 10 million m^3 towards the north-east.

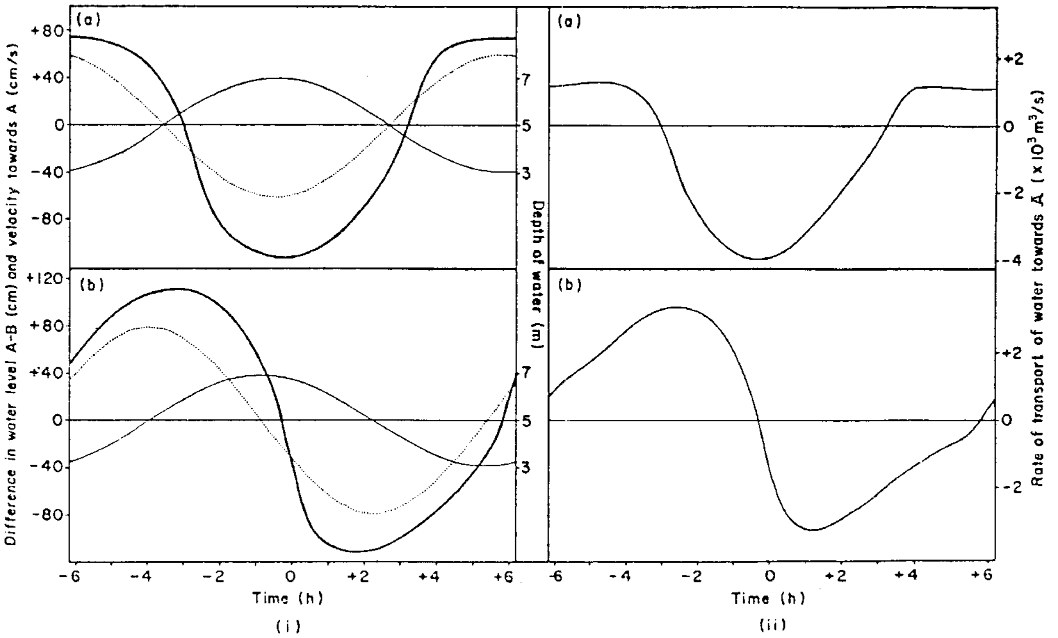

FIG. 8(a). Computed difference in water level between the two ends of a channel (dotted line), and velocity (thick line) and depth (thin line) of water at a position midway along the channel.

FIG. 8(b). Computed transport of water at a position mid-way along the channel. (i) Case Y (phase difference zero), (ii) Case Z (amplitudes equal).

It would appear, therefore, that in the Menai Straits the residual flow towards the south-west may be attributed to the tidal range at the north-eastern end exceeding that at the south-western end, and that the magnitude of this flow is, in fact, reduced by the phase of the tide being later at the north-eastern end than it is at the south-western end. It would be reasonable to suppose that similar residual flows exist in other tidal channels where the tidal range is significant in relation to the total depth, and where either the tidal ranges or the phase of the tides at the two ends differ.

Acknowledgments

I wish to thank the Lancashire and Western Joint Sea Fisheries Committee for permitting me to use their vessel *Thomas S. Richardson* to make current measurements, and the Hydrographic Department of the Ministry of Defence who cooperated in making current measurements and made their observations available to me. I should also like to express my thanks to all of my colleagues at the Marine Science Laboratories, Menai Bridge who assisted in making the observations, and who have made helpful suggestions on the dynamical aspects of the flow, and to Mr B. H. Rudall for assistance in solving the equation of motion by computer.

Marine Science Laboratories,
Menai Bridge,
Anglesey,
Wales.

1967 *November.*

References

Embleton, C., 1964. The deglaciation of Arfon and Southern Anglesey and the origin of the Menai Straits, *Proc. Geol. Ass.*, 75 (4), 407–430.

Harvey, J. G., 1967. The effect of weather on water level in the Menai Straits, *Deutsch. Hydrogr. Zeits.*, 20, (2), 54–58.

Jones, P. G. W. & Haq, S. M., 1963. The distribution of phaeocystis in the Eastern Irish Sea, *J. Cons. perm. int. Explor. Mer*, 28 (1), 8–20.

Lee, A. J., Bumpus, D. F. & Lauzier, L. M., 1965. The sea-bed drifter, *ICNAF Research Bulletin*, No. 2.

Proudman, J., 1953. *Dynamical Oceanography*, Methuen, London.

Erratum

Harvey, J. G., 1968. The flow of water through the Menai Straits, *Geophys. J. R. astr. Soc.*, **15**, 517–528.

The captions to Figs 7 and 8 should read as follows:

(i) (ii)

Fig. 7(i). Computed difference in water level between two ends of a channel (dotted line), and velocity (thick line) and depth (thin line) of water at a position mid-way along the channel.

Fig. 7(ii). Computed transport of water at a position mid-way along the channel.

(a) Neap tide conditions, (b) mean tide conditions, (c) spring tide conditions.

Fig. 8(i). Computed difference in water level between the two ends of a channel (dotted line), and velocity (thick line) and depth (thin line) of water at a position midway along the channel.

Fig. 8(ii). Computed transport of water at a position mid-way along the channel.

(a) Case Y (phase difference zero), (b) Case Z (amplitudes equal).