THE OCEANOGRAPHY OF FALMOUTH HARBOUR

by

T.J. Sherwin

on behalf of

NRA (South West)
Manley House
Kestral Way
EXETER
Devon

REPORT U93-4

MARCH 1993

UNIT FOR COASTAL AND ESTUARINE STUDIES
MARINE SCIENCE LABORATORIES
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SUMMARY

The oceanography and circulation of the southern part of Falmouth Harbour have been studied using data collected during September 1990 and May/June 1992. Tidal currents are relatively small (M2 is typically <35 cm s^{-1}) so during summer, and provided winds are weak, the water column can be stratified for much of the spring/neap cycle. On spring tides, however, fast flows exist in the deep channel at the entrance to the harbour, which is then vertically mixed. The spring tide excursion in the deep channel can carry water from opposite the Percuil River to above Penarrow Pt (3.4 km) on spring tides and to about St Mawes Bank (1.7 km) on neap tides. However, on the Falmouth side the spring tide flood excursion is much shorter than that of the neap tide. Dye released at the proposed outfall site on a spring tide was unable to penetrate the turbulent water of the main channel and became trapped at the entrance to the Penryn River. On neap tides however, when the water is stratified, the deep channel is not a barrier and material from the Falmouth side can be carried onto St Mawes Bank, even if the wind is from the east. This may be of concern to the shell fisheries there since LW neaps coincides with the peak early morning discharge from the outfall.

On the ebb tide material is carried into Falmouth Bay where large surface shears exist which significantly disperse and dilute it before it is drawn back into the harbour. There appears to be no significant threat to Gyllyngvase Bay or the Percuil River from the proposed outfall.

CONTENTS

1 INTRODUCTION

This is a report of an investigation into the physical dynamics of the Falmouth harbour estuarine system and the neighbouring coastal waters. The original site work was conducted by Andrews Hydrographics (1990) and Wallace Evans (1992), hereafter called AH and WE respectively.

The AH survey took place in September 1990 and involved 11 fixed stations (12 h duration) conducted on spring and neap tides, three recording current meters deployed in Falmouth bay, drogue track releases designed to investigate circulation in the harbour entrance, tide gauges and a meteorological station (Fig. 1). Other work involving an investigation of pollutant loads has been ignored. Whilst AH investigated the system as a whole, WE concentrated their work (in May and June 1992) near the proposed outfall site (at 183190E 32141N about 625 m from the Falmouth shore, Fig. 2). Besides meteorology and tidal levels their work mainly involved dye and drogue releases from the proposed outfall, along with a current meter and thermistor string deployment in Gyllyngvase Bay. In addition a continuous spore release was made from the proposed outfall, where a single 13 h fixed station measurement was made.

Chapter 2 is a discussion of the physical characteristics of the harbour based on Admiralty data; this is followed in Chapter 3 by a description of the tidal regime, both inside and outside the harbour, based on AH fixed station data and drogue tracks; Chapter 4 looks at several fixed stations in more detail and reviews the variations in velocity and density structure between springs and neaps. In Chapter 5 there is an analysis of the WE drogue and dye tracks, where the data are superimposed to reveal insight into processes. Chapter 6 discusses the results from the WE spore release and, finally, Chapter 7 is an overview of the most important aspects of the oceanography of the harbour, in particular with respect to the proposed outfall location.

Note that the name "Gyllyngvase Bay" (which does not appear on any map or chart), has been given to the small bay on the western side of the harbour entrance to distinguish it from Falmouth Bay which is much larger.

2 PHYSICAL CHARACTERISTICS OF THE HARBOUR

Falmouth Harbour is a complex estuary system (Figs 1 and 2). The main central section (Carrick Road) is about 7 km long from Pendennis Pt to Turnaware Pt and about 2 km wide. Most of Carrick Road is less than 5 m deep at the lowest astronomical tide (LAT), but it contains a narrow meandering centre channel with depths of order 25 m. There are several large creeks attached to Carrick Road (at Falmouth, St Mawes and Restronguet), and there is a major branching estuary system above Turnaware Pt which extends as far as Truro. The distance from Pendennis Pt to Truro along the principal axis of the Harbour is about 15 km, and total surface area at MHWS is about 24×10^{6} m^2. The complicated nature of Falmouth Harbour makes it difficult to summarise since it is not well suited to simple analytical techniques.

The tidal amplitude measured by AH at Nare Head (National Grid reference SW 915370) is reasonably large with M2 ≈ 1.70 m and S2 ≈ 0.57 m (Table 1). From Admiralty data, the tidal range is 4.7 m at mean springs and 2.3 m at mean neaps (see Chart 32). Chart datum (CD) is 2.91 m below Ordnance Datum (Newlyn).

The volumes of discrete sections of the harbour at the highest and lowest astronomical tides (HAT and LAT) were calculated from Chart 32 using the method described in Appendix I. The mean volume of water in the harbour is about 164×10^6 m^3 (from Table 2), of which about 80% comprises the Carrick Road and only 8% the Truro and Fal River system. (The rest is located in the major creeks attached to the Carrick Road). From the cumulative volume curves (Fig. 3) it is estimated that the tidal excursion ranges from 3.0 km (springs) to 1.6 km (neaps) at the seaward end of the Carrick Road.

The flushing times, T_F of the system as a whole and of various creeks have been calculated in Table 2 using

$$T_F = \frac{V_H}{(V_H - V_L)} \text{ tidal cycles} \qquad (1)$$

where V_H and V_L are the volumes of water at high water (HW) and low water (LW) respectively; and it is assumed that there is perfect exchange with the sea so that water leaving the harbour on the ebb does not return on the flood. This assumption means that (1) probably gives faster flushing estimates than actually exist. The shortest flushing time occurs during the largest tidal range (between HAT and LAT) when it is about 1.9 tidal cycles. Flushing times for other tidal ranges were calculated by interpolating the tidal volumes against tidal height. Between mean springs and mean neaps T_F increases from 2.2 to 4.3 tidal cycles. Thus, from these calculations tidal flushing has a marginal effect on background bacteria levels, but is significant in flushing more slowly decaying pollutants such as nutrients.

Climatic Wind Data

Admiralty (1977) present climatic wind data for Plymouth and Falmouth decomposed into percentage of observations from 8 points of the compass on a monthly basis (Fig. 4). The annual mean speeds are 10 knots (0900 h) and 11 knots (1500 h) at Falmouth and 9 knots (0900 h) and 12 knots (1500 h) at Plymouth. The distribution of winds at Falmouth shows relatively little variation on either an annual or a diurnal basis, although in July there is a slightly higher proportion of afternoon winds from the south. At Plymouth, however, the contrast is quite marked with 45% of all July afternoon winds coming from the south and south-west, compared with only 25% in the morning. A diurnal variation of such magnitude can only be explained in terms of an onshore sea breeze, which at Plymouth can be generated by the large land mass of Devon behind it. The Cornish peninsular, however, is very narrow and presumably cannot cause significant sea breezes to occur. Thus, unlike some other parts of the south-west peninsular, sea breezes are not an important aspect of the local wind field at Falmouth.

3 TIDAL CURRENTS

This chapter contains a review of surface tidal currents. Data from AH 12 h fixed stations and Admiralty tidal diamonds on chart 32 were subjected to a simple tidal 'harmonic' analysis in which the only constituents are assumed to be the mean flow and harmonics with periods of 12.42 h, 6.21 h and 4.14 h. At every station, spring tide observations were used with the time origin being local HW. The currents shown in Fig. 5 were subsequently reconstituted from the main constituents and scaled to give predictions of the mean tidal flow (equivalent to a tidal range of 3.5 m). The plots are not entirely consistent since the AH data include mean flows, which can vary on a 2-3 day time-scale, and employ different methods of measurement (specifically between the two data sources). Nevertheless they give a good indication of local flows.

Overall the tidal currents during a mean tidal range are relatively small, and only at Turnaware Pt do they exceed 50 cm s^{-1}. Relatively fast currents are also found in the mouth of the harbour and at the entrances to Restronguet Creek and the River Fal which have restricted entrances. Off Falmouth, in the deep water near the proposed outfall (Sta. FS2), the mean flood current (48 cm s^{-1}) is larger than the ebb (37 cm s^{-1}). The same is true at Turnaware Pt, where the maximum flood is 62 cm s^{-1}, compared with an ebb of 41 cm s^{-1}, but at Restronguet Pt the ebb (37 cm s^{-1}) is a little stronger than the flood (32 cm s^{-1}). These asymmetries in the tidal curve are probably due to variations in local friction.

At Sta. FS2, the M2 current amplitude is 35 cm s^{-1} which suggests a tidal excursion of about 5 km, which is significantly further than that estimated from the cumulative volume curve. Thus material released at LW could be carried as far as Restronguet Pt. However, the calculation neglects the Lagrangian nature of tidal advection - M2 at Sta. FS5, and further into the Carrick Road, has a semi-major axis of about 10 cm s^{-1} and hence an excursion of about 1.4 km. On this calculation the maximum excursion extends only to Penarrow Pt.

Circulation patterns at the mouth of an estuary are important in determining its flushing characteristics. With this in mind, we look at the circulation in Falmouth Bay, which can be derived from drogue track observations by AH (Fig. 6) during spring tides. The tide in the English channel south of Falmouth propagates eastward as a progressive wave, so at HW there is a maximum eastward flow around St Anthony Head, with spring tide current speeds of order 50 cm s^{-1}. At this time there is slack water in Gyllyngvase Bay. By HW+2 the eastward flow has ceased and flow in the region is concentrated to the ebb outflow which meanders out (almost as a jet) along the deep water channel towards the SSE. However, by HW+3 the offshore flow has begun to set in towards the west although the ebb waters leaving the harbour are carried at least one km away from Gyllyngvase Beach. This pattern continues until about LW.

Throughout the ebb, currents in Gyllyngvase Bay are weak (see also Fig. 5), but as the flood begins they start to flow eastward across the mouth of the bay. From the drogue tracks at HW-6, it would appear that this flow is initially caused by a residual clockwise vorticity in Falmouth Bay with currents of order 20 cm s^{-1}. (In a depth of $h = 10$ m, and using a drag coefficient of $C_D = 2\times10^{-3}$, the decay time for this circulation is $h/C_DU \approx 7$ h, so the vorticity decelerates more slowly than the slope driving the main flow which generated it). During much of the flood (probably until HW-2) water enters the harbour from the western side with that part closest to Pendennis Pt being carried past the outfall site and into the Penryn river, while water further offshore is advected towards St Anthony Head before being deflected northward and into the Percuil river. As HW approaches, the eastward offshore flow increases in strength and its influence seems to extend almost inside the harbour mouth. Throughout the flood, there is an eastward flow past Gyllyngvase Bay, which contrasts with the slack water during the ebb and gives rise to a net eastward (Eulerian) residual in the bay.

The basic circulation on neaps (Fig. 7) is similar to that described above, but with lower velocities and two other important differences. In the first place, the outflow is weaker and does not form a jet so that it tends to be carried westward around Pendennis Pt - it may eventually feed into Gyllyngvase Bay. Secondly, the weaker offshore currents do not set up an eddy at LW. Consequently, there appears to be less tendency than on spring tides for the flood to be drawn into the harbour from the west (although there were fewer neap tide drogues from which to base this interpretation). Thus the eastward residual in Gyllyngvase Bay appears to be much weaker on neaps. This observation is borne out by the recording current meters deployed by WE just outside the bay. In particular, the residual in the bottom waters (6.8 m from the seabed) was negligible during neaps but of order 6.5 cm s^{-1} during springs. The residual from the instrument deployed at 1.5 m was not so well correlated with the spring-neap cycle although it appeared to show a similar trend.

In conclusion, on spring tides it appears that much of the ebb tide water is ejected well to the south of St Anthony Head, whilst on the flood the harbour is replenished by water flowing from the west through Falmouth Bay. The Penryn River is filled by inshore water that flows across the mouth of Gyllyngvase Bay, whilst the Percuil River receives water from further offshore which turns inward on the eastern side of the harbour. On neap tides the outflow is not as strong, and material leaving the harbour on the ebb will be carried into Falmouth Bay. The inflow pattern has not been as extensively measured as on the springs but is is possible that on neap tides water enters the Percuil River from the east around St Anthony Head.

4 FIXED STATION DATA

The distribution of tidal currents in Falmouth Harbour, described in the preceding chapter, was derived to a large extent from fixed station surface current observations. In this chapter we consider the fixed station data further and, in particular, look at the vertical variation in velocity and density at three stations in the lower part of the harbour. We start, however, by considering the variation in depth mean salinity along the axis of the harbour.

The depth mean HW and LW salinities at spring tides have been calculated for the AH stations sited in the deep water channel in September 1990 (Fig. 8). The observations were made over a 14 day period when the mean river flow into the harbour, calculated from NRA data using the method described in Appendix II, was 1.05 $m^3 s^{-1}$ (±0.43) $m^3 s^{-1}$ (see Table 3 for station data including flows on the observation days). This is considerably less than the annual mean (5.9 $m^3 s^{-1}$) and close to the Q_{95} flow (Table 4). The relatively small standard deviation indicates that the flow was effectively steady during this period so that it is reasonable to compare observations made on different days. It is not surprising, given the low flows, that the mean salinity varied by less than 0.6 psu between Pendennis Pt and Turnaware Pt. Vertical salinity stratification throughout the Carrick Road was small, and generally less than the resolution of the recorded data.

A salinity flushing time for Carrick Road can be estimated as:

$$T_F = \frac{V}{Q}\frac{(S_0 - S)}{S_0} \qquad (2)$$

where V is the volume of Carrick Road and the lower tributaries (1.50×10^8 m^3), Q is the mean freshwater inflow into Falmouth Harbour, S_0 is the mean salinity at Sta. FS2 and S is the mean salinity in Carrick Road. For the first half of September 1990 Q = 1.05 $m^3 s^{-1}$ (Appendix II), S_0 = 35.23 psu and S = 35.045 psu, so T_F = 8.5 days. This is between 2 and 4 times as long as that estimated from the tidal volumes, and may be a more accurate estimate of the time it takes for material to be flushed from the head of Carrick Road, since it does not include the assumption of total mixing of the incoming tide within Falmouth Harbour.

From Fig. 8 it is possible to infer the tidal excursion for spring tides based on the distance between the HW and LW salinity lines. The excursion, X_e, is estimated to range from 3.4 km near the mouth to 3.0 km near the head of the Carrick Road. Thus material released near the proposed outfall site may be advected inwards beyond Penarrow Point on mean spring tides. The equivalent velocity, found from $u = \pi X_e/T$, where T is 12.42 h, is 24 cm s^{-1}. On mean neaps the equivalent scales are 1.7 km and 12 cm s^{-1}, which suggests that LW discharges will not be carried beyond St Mawes Bank. These values are similar to those computed from the cumulative volume curves.

The dynamics of the seaward end of Falmouth Harbour can be better appreciated by examining the fixed station data from the surface and near bottom (typically 1.5 to 2 m from the sea bed). AH did not record velocities less than 5 cm s^{-1} so there is some patchiness in some of the vector plots (Figs 9 and 10).

Station FS2 (Fig. 9) was situated in the deep water near the mouth of the Percuil River. It is noticeable that the spring-neap difference in tidal velocities (about a factor of four) is twice that expected from elevation (factor of two). (On spring tides, the surface velocity range - i.e. difference between maximum flood and ebb velocities - was 120 cm s^{-1}, whilst on neaps it was only 29 cm s^{-1}). This inconsistency was not repeated at Sta. FS5 (Fig. 10), in the Carrick Road, where the surface velocity range was 46 cm s^{-1} on springs and 26 cm s^{-1} on neaps. A detailed examination is beyond the scope of this report, but it seems unlikely that the situation at Sta. FS2 was simply caused by the variation in bottom drag characteristics between the shallow and deep water across the harbour mouth. A more likely explanation can probably be found in the generation of non-linear accelerations and the clockwise eddy created in Falmouth Bay on spring tides. As discussed in the preceding chapter, this cell results in water being swept eastward across the mouth of the harbour on the flood, which is likely to be deflected into the harbour by St Anthony Head. This may explain the high flood tide velocities, if not those of the ebb which should be unaffected by circulation in Falmouth Bay.

The neap tide surface currents at Sta. FSWE (Fig. 11), sited in the shallow water due west of Sta. FS2, were about twice as large as those in the deep water station, whilst the corresponding bottom currents were about 50% larger - this comparison takes into account the difference in tidal ranges. There seems to be no ready explanation for these differences which, along with the spring-neap variation at Sta. FS2, suggest that there are large lateral shears across the mouth of the harbour, with relatively stronger currents being found on the Falmouth side during neaps and on the St. Mawes side during springs.

During the period of strong spring tide currents at Sta. FS2 the water column was effectively mixed. Further into Carrick Road at Sta. FS5, however, the water was more stratified, with a temperature difference of order 0.5° C, presumably because tidal currents (and hence tidal mixing) are much weaker there. On 4th Sept 1990 the wind (mean velocity 4.1 m s^{-1} from 340° T) seems to have set up a vertical circulation with surface waters blown southward at about 9 cm s^{-1} down Carrick Road and a return flow of 7 cm s^{-1} at depth. Wind driven currents of this magnitude would be strong enough to overcome tidal currents on neap tides.

Apart from Sta. FS2 on spring tides, most of Falmouth Harbour exhibited sufficient vertical stratification to suppress vertical eddy viscosity and allow significant vertical shear to occur. The implication for the fate of pollutants in the harbour is that in summer they may become trapped in the surface layers and susceptible to wind forcing.

5 DROGUE AND DYE TRACKING

The discussion of currents in the preceding chapters has been based on Eulerian (current meter) measurements. However, circulation at the mouth of the harbour in the vicinity of the proposed outfall can only be properly assessed by studying the Lagrangian motion of dye and drogue/floats. In this discussion the dye will be treated as a Lagrangian tracer, rather than as a measure of diffusivity.

In total, WE made eight releases at the end of May and beginning of June 1992, covering four phases of the tide for neaps and springs. On each occasion rhodamine dye was released near the proposed outfall along with several drogue/floats located at either 1.5 m or 3 m depth. Four experiments have been studied in detail (Figs 12 to 15 and Table 5), covering LW and mid ebb releases on springs and neaps, which summarize the circulation at times when potentially sensitive areas could come under threat. In the figures, dye patches have been drawn by choosing an appropriate arbitrary contour to indicate their general shape and position. In each case drogues have been selected in pairs (at 1.5 m and 3.5 m) that span the dye patch.

LW Release (Neap Tides, Fig. 12)
The release was made in the early morning (0420 h) and during the observation period winds were relatively calm (< 3 m s^{-1} from 150°). No CTD data were collected, but even 4 hours after the release most the the dye was concentrated in the upper 3 m so it seems likely that the water column was stratified. Dye and drogues were carried northward with a maximum speed of about 25 cm s^{-1}. The deep channel does not seem to have affected the passage of dye or drogues which tracked across it until at HW the dye and three of the drogues ended up on St Mawes Bank; the exception was the shallower western drogue which did not cross the 10 m line.

The trajectories of the three eastern drogues seem to run parallel to the coastline until slack water, which suggests that whilst surface layer is decoupled from the deeper water, it is nevertheless constrained by continuity to follow the coastline. As long as the drogues were in relatively deep water there was little vertical shear, but as soon as they crossed onto St Mawes Bank they encountered a shear of about 4 cm s^{-1} in 1.5 m with the deeper drogue moving more slowly, so that at the end of the experiment it was about 400 m to the south of its shallower counterpart. The reason for this shear is not known for certain since no CTD profiles were made; however, it may suggest that St Mawes Bank was more stratified than the channel or, since the drogues travelled slower over the bank and the depth of water was only about 6 m, that the 3 m drogue was in the bottom boundary layer. At HW slack the drogues were subsequently carried eastward (into the wind) towards the shore on the St Mawes headland. Throughout the experiment the drogues remained closely attached to the dye, indicating that wind drag on the floats was small. It is noticeable that so long as the drogues were tightly bunched the dye remained compact, but that as they encountered the shear over St Mawes Bank so the dye became elongated (as expected from shear diffusion theory).

LW Release (Spring Tides, Fig. 13)
This experiment started at 0133 h (at LW) on 4th June 1992 and dye and drogue tracks have been plotted until the following HW. Wind speeds were relatively high at first (about 6 m s^{-1} from 140°), but later dropped to about 2 m s^{-1}. A CTD cast taken in the entrance to Penryn river revealed that the water column was mixed down to 6 m (the sea bed).

This time the dye probably became rapidly mixed through the water column (although no observations were made to confirm this) and it then remained in the shallow water on the Falmouth side of the harbour for the first two hours as it moved north with a speed of about 22 cm s^{-1}. During this period the drogues followed a similar path. By 0500 h drogues and dye had arrived over Falmouth Bank, due north of the docks, and subsequently the dye became stretched in two as most of it was carried in to Penryn river with a small amount continuing northward into Carrick Road. It appears that by HW-4 there is a substantial inflow into Penryn river from its northern side, which is consistent with the divergence in the current vectors observed for HW-2 in Fig. 5b. Later patch positions suggest that the dye became trapped in the entrance to Penryn River having been pushed southward by water which, having followed the path of drogue 4, entered the river from the north.

The exception to this pattern was the eastern surface drogue 3, which early on had a slightly more northerly route than its deeper counterpart and, although there was no significant lateral shear, was eventually caught up in the faster current in the deep water of the Carrick Road to be carried north of Mylor Creek. The drogue took a short cut across the bend opposite Penarrow Pt and subsequently was unable to re-enter the deep water channel further north. This suggests that a front of some sort existed along the edge of the channel, possibly caused by differences in salinity.

Mid-ebb release (neap tide, Fig. 14)
Mid ebb releases have been selected for detailed analysis because they seem to pose a greater threat to Gyllyngvase Beach than the HW releases, which were simply carried out to sea. This release started at 0451 h on 28th May 1992 when the wind about 5 m s^{-1} from 185° T. However, between 0600 h and 0800 h the wind shifted temporarily to 4 m s^{-1} from 140° T before returning to 185° T. Although no CTD casts were conducted, the water column seems to have been stratified since vertical profiles reveal that the dye remained trapped in the surface 3 m until 0815 h at least. During the first two hours, when the dye was transported southward into Falmouth Bay, it remained fairly circular in shape. However there was a nevertheless significant surface shear since the 1.5 m drogues travelled about 5 cm s^{-1} faster than the 3 m drogues, possibly due to a density flow since this shear is in the opposite sense to any wind effect. By slack water (0900 h) both drogues and dye had encountered strongly divergent water so that by 1100 h both dye and drogues were stretched out several kilometres. At no time was Gyllyngvase bay threatened by the dye.

Mid-ebb release (spring tide, Fig. 15)
On this occasion dye was released at 0804 h on 31st May 1992 when the

wind was fairly light (3.5 m s^{-1} from 180°). The dye remained in the surface 5 m for the first 1.5 hours until after 0940 h (patch E). However, by 1045 h (near patch F) it had apparently become vertically mixed whilst at the same time there had been an increase in surface temperature from 15.2 °C to 15.5 °C, and and a decrease in temperatures at 14 m from 14.3 °C to 13.5 °C. Thus a front seems to have existed in the vicinity of patch E, and this may have created a vertical circulation cell to cause the mixing of the dye. Subsequent elongation of the patch was probably due to wind driven vertical shear associated with stratification in the deeper water.

During the latter part of the experiment there appears to have been a large shear in the upper 1.5 m which was decoupled from the motion at 3 m depth where the two drogues kept the same distance apart throughout the observation period. By the end, at about 1430 h, the surface drogues were about 1.6 km apart and straddled the mouth of Gyllyngvase Bay. There is no doubt that this separation is an accurate reflection of water movement, because the dye patch had also been stretched by a comparable amount. Furthermore the highest dye concentrations were observed near the western end of the patch, which is consistent with the positions of the two deeper drogues. However, this picture does not simply describe a surface slab sliding over deeper water because the western surface drogue remained close to the deeper drogues. Thus the surface waters diverged, for reasons which are not clear, but which may be either due to wind shear or linked to the front.

In summary, drogues and dye were carried out into the deeper waters of Falmouth Bay where they encountered the eddy generated by St Anthony Head. Although this eddy subsequently carried water in towards Gyllyngvase bay, six hours after the release, the beach itself was never threatened.

6 SPORE RELEASE

Spores of the bacterium *B. globigii* were released continuously from the proposed outfall site between 0415 h and 1730 h on 7th June 1992. LW was at 0350 h, the tidal range 3.6 m and winds were light (generally < 4 m s^{-1}). During the first hour the spores were released at a rate of 3.3×10^{10} s^{-1}, but for the remaining 12 h 15 m the release rate was 4.1×10^{9} s^{-1}, so that the total quantity of released spores was 3×10^{14}. This is the same magnitude as the total daily release of coliforms projected for the year 2021 (1.1×10^{14} to 2.6×10^{14}) so, since the decay time for coliforms (typically 12 h) is the same as the spore release time, the spore concentrations should be of similar magnitude to those expected for coliforms in the future. In addition to the spore, several spot dye releases were made to mark its trajectory so that locally intensive observations could be made. Elsewhere observations were made over an evenly distributed grid extending from Falmouth Bay to Restronguet Pt.

Spore release data are difficult to interpret because the inefficiency of sampling technique means that relatively few observation points can be used.

As a result, peaks in concentration are easily missed, and only on the largest of scales is it possible to contour the data. As an illustration of this the concentrations in a dye patch in Falmouth Bay (marked 4.5 h, run 2 in WE) were (178, 710, 790, 1200, 1900), which has a mean of 956 and standard deviation of 641 or a signal to noise ratio of about 3:2. These observations were made over a distance of 800 m, much less than the spacing of the sampling grid.

Despite these reservations, the spore data are useful because they can provide insights into long term Lagrangian trajectories. Simple outfall dynamics theory indicates that for pollutants with short decay times (say less than 12 h), two regions of peak concentration occur when the tidal currents are rectilinear, which are created at HW and LW slack (and are thus located at either end of the tidal excursion). These peaks can be seen (in WE) in the spore data plots centred on HW and LW. At HW, concentrations are greatest in the lower part of Carrick Road extending as far as Penarrow Pt. In general, higher concentrations were found in the main channel, although 6 h from the start a count of 100 spores per 100 ml was observed on St Mawes Bank. Similarly at LW a peak was observed about 1 km offshore in Falmouth Bay. In general the peak concentrations in Falmouth Bay seem to have been more diffuse than their counterparts in Carrick Bay.

Spore counts north of Penarrow Pt were always very small, whilst in the Penryn and Percuil Rivers and on Gyllyngvase Beach maximum values were only of order 20. Given the approximate correspondence between spore and future coliform counts these values are small and suggest that these regions are not threatened by the proposed outfall.

7 DISCUSSION AND SUMMARY

Falmouth Harbour is a complicated estuarine system and the discussion concentrates only on the Carrick Road, Harbour entrance and Falmouth Bay. It should be noted that the data on which this report is based were collected in summer 1990 and 1992 during relatively calm weather and low river flows and so are not representative of the annual cycle.

The flushing time, T_F, of the harbour has been estimated in two ways. Consideration of tidal hydraulics suggest T_F varies from 2 days (springs) to 4 days (neaps). However, salinity observations and river flow measurements suggest T_F = 8 days. It seems likely that this longer period is more appropriate since it is based on the time it takes to replace the observed volume of freshwater in the harbour. However, exchange with Falmouth Bay appears to be very efficient, so that flushing times near the harbour entrance are probably closer to one tidal cycle. It is also likely that in winter, when freshwater flow is higher, total flushing times are much less than 8 days.

The data reveal that Falmouth Harbour can become stratified in summer. This point is emphasised because the data reports say that stratification is weak or negligible. However, a vertical temperature difference of, say, 1 °C is significant for two reasons. Firstly, it shows that there is insufficient turbulent kinetic energy in the system to mix the water column and, secondly, the associated buoyancy gradient suppresses mixing processes. Stratification is significant in marine pollution problems because where it occurs effluent will be trapped in the sea surface, its own inherent buoyancy reinforcing the effect. It is then susceptible to wind forcing and also poses a greater threat to water contact users. However bacteria in surface waters will die more rapidly from UV radiation, and surface shears (and hence horizontal diffusion) may be greater than when the water column is mixed, so that the net effect of stratification may be beneficial. Although most of the observations revealed that the water column was stratified it can become mixed in the mouth of the harbour during spring tides and when it is sufficiently windy.

The circulation in the mouth of the harbour varies considerably between spring and neap tides. On springs a clockwise eddy is set up in Falmouth Bay after LW so that on the flood there is an eastward flow towards St Anthony Head which seems to cause unusually strong currents to flow into the harbour along the deep water channel. These currents ensure that the water in the channel is mixed, and because of this it seems to form a barrier to material discharged on the Falmouth side. During the early part of the flood water enters Penryn River from the south, but later on the inflow is stronger on the northern side. As a result the LW effluent concentration peak (defined in Chapter 6) will be carried northward, and may be trapped at the entrance to the Penryn River. On the ebb, water in the mouth of the harbour is ejected well out into Falmouth Bay where it is efficiently dispersed and mixed. However, some of this water may re-enter the harbour on the subsequent flood having been carried round the clockwise eddy in Falmouth Bay.

On neap tides, however, flow past St Anthony Head at LW is not fast enough to create the offshore eddy and consequently there is a more uniform flow across the harbour entrance on the flood. With weaker tidal currents, the harbour entrance remains stratified and consequently it is possible for the LW effluent concentration peak to cross the main channel. The relevant dye release ended up in the sensitive waters over St Mawes Bank, and there may be reason for some concern about this since LW neaps coincides with the morning peak flow through the sewer to the outfall. On the ebb, the HW peak will be transported directly into Falmouth Bay and, in the absence of the clockwise eddy, is not expected to return to the harbour on the flood.

The above discussion indicates a paradox, because although the tidal excursion is much greater in the main channel on springs (3.4 km) than it is on neaps (1.7 km), for effluent discharged on the Falmouth side the reverse seems to be the case, at least on the flood tide. Consequently it should be difficult for effluent to penetrate the Carrick Road to the north of St Mawes Bank, a fact which is supported by the spore release since hardly any spores were carried very far in this direction. Overall, the spore release served to confirm the picture given above, and of the three or four most sensitive locations (Gyllyngvase Beach, Penryn and Percuil rivers and St Mawes bank) only the last had a spore count in excess of 100 per 100 ml.

One factor which is impossible to control during site investigations is the weather, and most of the reported observations were made during relatively light winds. The main effect of stronger winds will be to enhance the vertical mixing of the water column. As indicated above, with the water vertically mixed horizontal diffusion is much smaller, because vertical shear (of horizontal currents) is inhibited, and bacterial decay times are increased. Under windy conditions it is likely that the enhanced vertical mixing will cause peak initial concentrations to be less, but that over longer periods of time the effluent will be diffused into a relatively smaller volume of water. It is probable, however, that the LW (neap tide) peak will not then be carried onto St Mawes Bank because it will be coupled to deep water. In general, the smaller horizontal diffusion coefficient means that the effluent should be less likely to encroach on the coastline when it is windy, given the length of the outfall.

Not all the data collected by AH and WE have been used in this analysis, but the omissions are not considered critical. Two extra things that would have been useful, however, are: i) areal CTD surveys of the whole harbour and Falmouth Bay on springs and neaps and ii) concurrent fixed station measurements across the mouth of the harbour (say at the proposed outfall and in the deep channel) during spring and neap tides.

Finally, it should be stated that the quality of data reporting by the survey companies was not particularly good, particularly by WE who, by including a plethora of irrelevant and duplicated information, made this work more difficult than it need be. There is a need for the survey companies to realize the importance of making accurate and regular density measurements in places where the tides are weak, such as Falmouth Harbour, and of reporting their results to two decimal places. It would also have been very helpful if the data had been provided in digital form.

Acknowledgements

The assistance of Dr P.B. Murray in several aspects of this work, including preparing many of the figures, is acknowledged with gratitude. Thanks are also due to staff of the NRA who carefully read a draft of this report and provided some helpful suggestions for improvement.

References

Andrews Hydrographics Ltd (1990). Fal and Helford Marine Environmental Survey, September 1990. [Report to South West Water Services Ltd].

Wallace Evans (1992). Falmouth Sewage Treatment Oceanographic Survey. Report No. 1H294/92/1, August 1992. Wallace Evans Ltd., Bridgend, Mid Glamorgan. [Report to South West Water Services Ltd].

Table 1

Tidal elevation constituents with amplitude larger than 5 cm at Nare Head (from AH)

Constituent	Period (h)	Amplitude (m)	Phase (lag)
O1	25.82	0.054	341
K1	23.93	0.089	120
2N2	12.91	0.196	115
$\mu 2$	12.87	0.231	176
N2	12.66	0.335	109
$\upsilon 2$	12.63	0.210	90
M2	12.42	1.704	146
S2	12.00	0.567	196
K2	11.97	0.204	194
M4	6.21	0.145	142
MS4	6.10	0.136	191

Table 2

Physical dimensions of Falmouth Harbour

Name	Length (km)	Surface area MHWS ($\times 10^6$ m^2)	Surface area LAT ($\times 10^6$ m^2)	Volume HAT ($\times 10^6$ m^3)	Volume LAT ($\times 10^6$ m^3)
Truro River [1]	6.0	2.34	0.48	8.35	0.05
River Fal [2]	8.1	3.00	0.85	12.81	6.09
Total	-	*5.34*	*1.33*	*21.16*	*6.14*
Restronguet Creek	3.2	1.57	0.07	4.84	0.00
Mylor Creek	1.7	0.25	0.02	8.03	0.00
Penryn River	3.4	1.79	1.14	12.05	3.41
Percuil River	5.5	2.09	0.83	9.87	1.25
Carrick Road	6.9	13.31	12.31	168.6	93.1
Total	-	*19.1*	*14.4*	*203.4*	*96.7*
Grand Total	-	24.4	15.7	224.5	103.3

Notes:
1 Truro River includes Tresillian River
2 From Turnaware Pt to Ruan Lanihorne

Table 3

Summary of Fixed Station Data in the Harbour entrance and Carrick Road

Station	Date	National Grid Position E	N	Tidal Range (m)	River Flow ($m^3 s^{-1}$)	Wind Speed ($m s^{-1}$)	Wind Dirn (°T)
Spring tides							
FS2	8/9/90	183763	32155	4.65	1.39	1.5	var
FS5	4/9/90	182910	33984	4.37	1.02	4.1	340
FS6	5/9/90	183918	35674	4.66	1.09	5.0	235
FS8	18/9/90	182659	36955	4.53	1.05	3.8	235
FS10	19/9/90	183411	38516	4.69	1.11	4.0	000
Neap tides							
FS2	14/9/90	183763	32155	2.35	0.77	3.0	085
FS5	12/9/90	182910	33984	2.94	1.23	2.7	095
FSWE	7/6/92	183173	32139	3.46	1.6*	1.9	115

* Estimated

Table 4

Freshwater Inflow to Falmouth Harbour

River System	ADF ($m^3 s^{-1}$)	Q_{95} ($m^3 s^{-1}$)	Q_{50} ($m^3 s^{-1}$)
Kenwyn	0.4	0.1	0.3
Kennal	0.8	0.2	0.5
Fal	2.3	0.4	1.5
Tresillian	1.1	0.2	0.7
Carnon	0.8	0.1	0.5
Allen	0.5	0.1	0.3
Total	*5.9*	*1.1*	*3.9*

Table 5

Summary of Drogue and Dye Information

LW (neaps)
Date: 24-05-92
Mean wind speed = 2.5 m s^{-1}, from 150 °
Tidal range = 2.41 m, LW = 0357 h, HW = 0950 h

Drogue no	1	2	3	4		
Start time	*0439*	*0431*	*0435*	*0433*		
End time	*1059*	*1106*	*1117*	*1113*		
Dye patch	Release	A	G	H	I	J	M
Time centre	*0404*	*0411*	*0516*	*0540*	*0622*	*0705*	*0922*

LW (springs)
Date: 04-06-92
Mean wind speed = 4.0 m s^{-1}, from 152 °
Tidal range = 4.39 m, LW = 0135 h, HW = 0710 h

Drogue no	1	2	3	4		
Start time	*0153*	*0154*	*0157*	*0156*		
End time	*0847*	*0850*	*0820*	*0841*		
Dye patch	Release	A	B	C	F	G
Time centre	*0133*	*0209*	*0235*	*0308*	*0458*	*0547*

Mid ebb (neaps)
Date: 28-05-92
Mean wind speed = 2.9 m s^{-1}, from 185 °
Tidal range = 2.84 m, LW = 0150 h, HW = 0817 h

Drogue no	1	2	3	4					
Start time	*0514*	*0503*	*0511*	*0504*					
End time	*1136*	*1131*	*1145*	*1137*					
Dye patch	Release	A	B	C	D	E	F	G	J
Time centre	*0451*	*0502*	*0508*	*0527*	*0556*	*0633*	*0711*	*0756*	*1127*

Mid ebb (springs)
Date : 31-05-92
Mean wind speed = 3.6 m s^{-1}, from 177 °
Tidal range = 3.90 m, LW = 0410 h, HW = 1051 h

Drogue no	1	2	3	4			
Start time	*0808*	*0800*	*0806*	*0805*			
End time	*1441*	*1430*	*1451*	*1432*			
Dye patch	Release	A	C	D	E	F	J
Time centre	*0740*	*0757*	*0809*	*0846*	*0955*	*1119*	*1421*

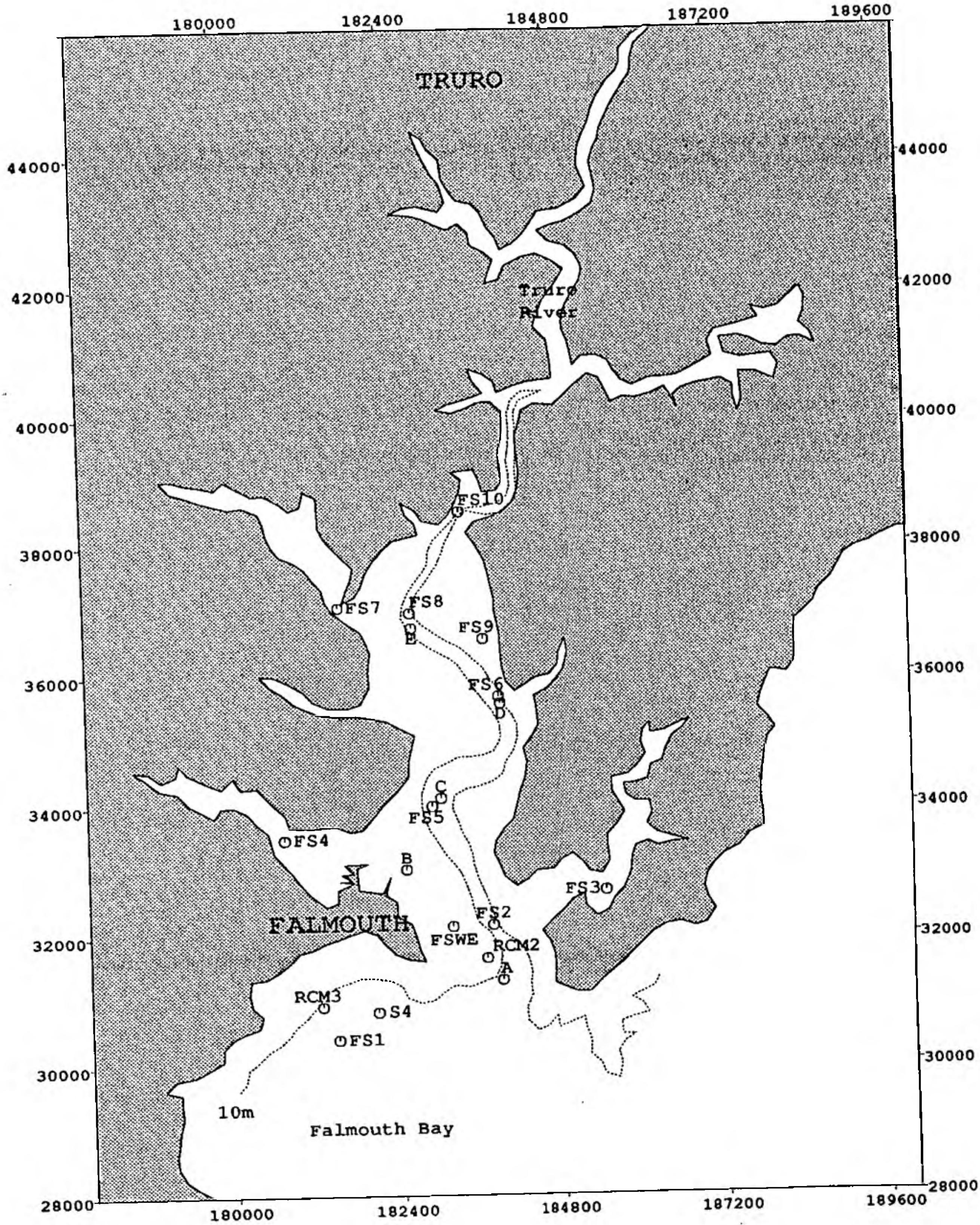


Figure 1. The Falmouth Harbour estuary system and the fixed stations discussed in the text. FS2 to FS10, and RCM2 and RCM3 were observed by AH; FSWE and S4 by WE; and A to E are Admiralty tidal diamonds. RCM2, RCM3 and S4 were recording current meters. The co-ordinate system is National Grid.

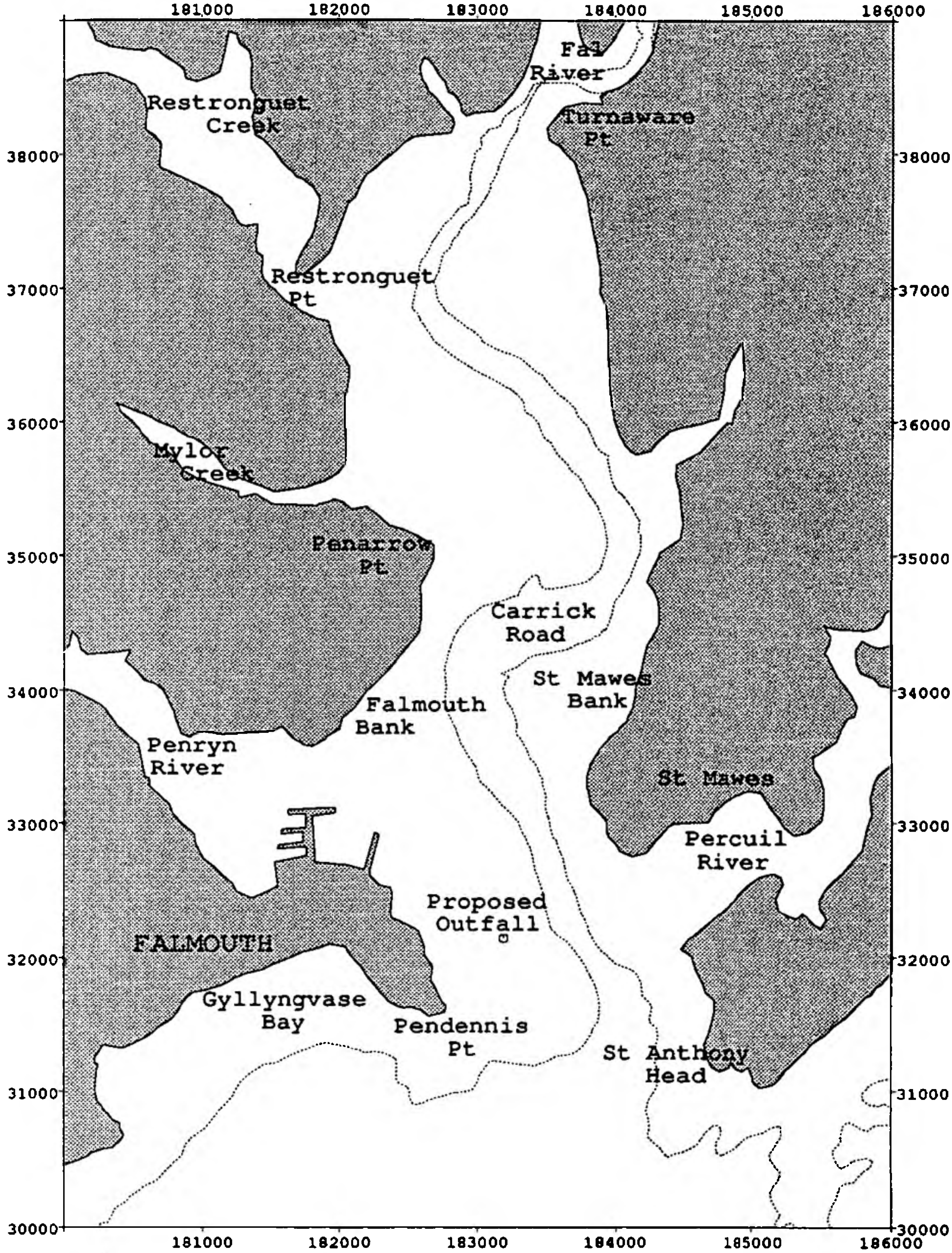


Figure 2. Falmouth Harbour with place names used in the text.

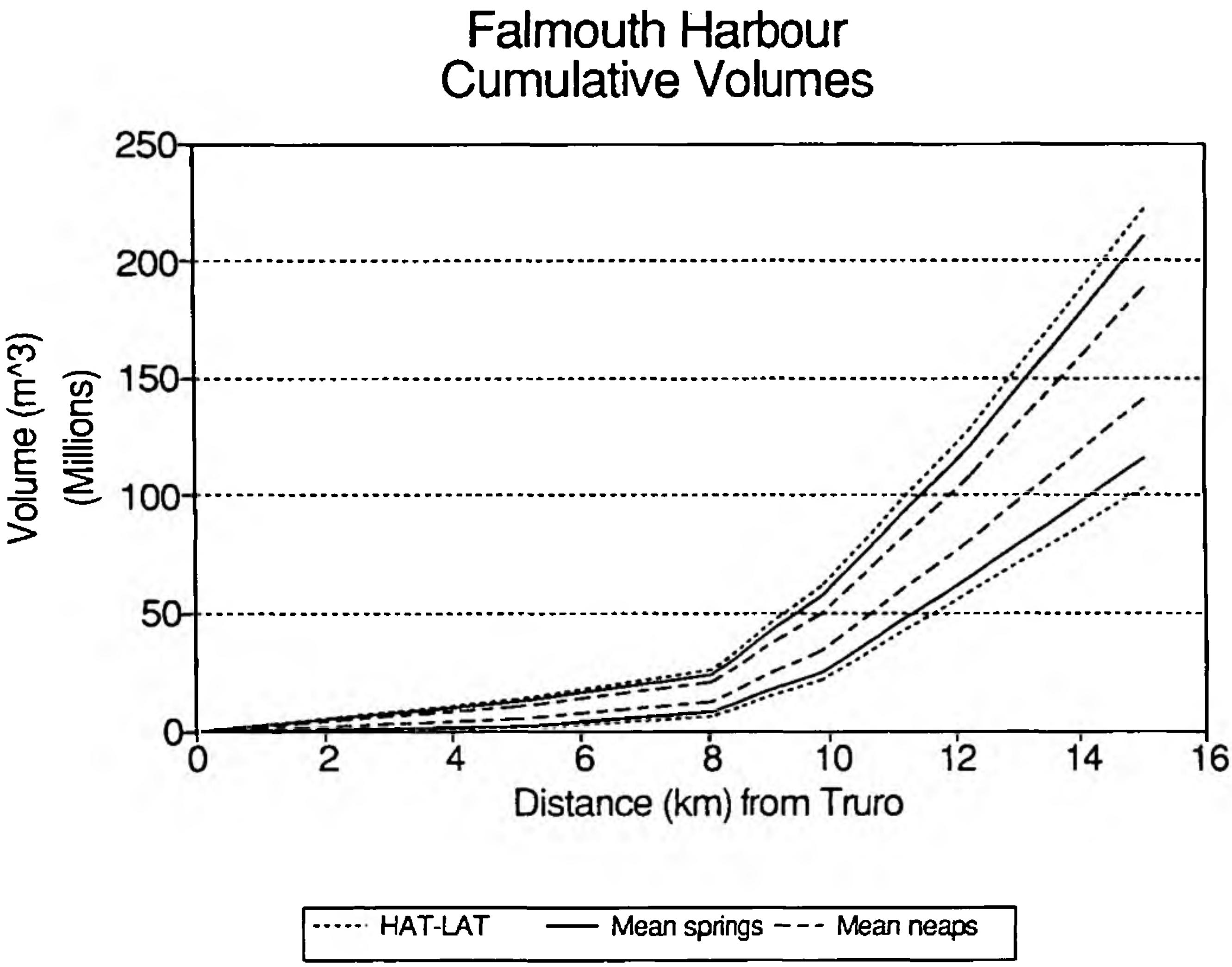


Figure 3. Cumulative volume curves in Falmouth Harbour.

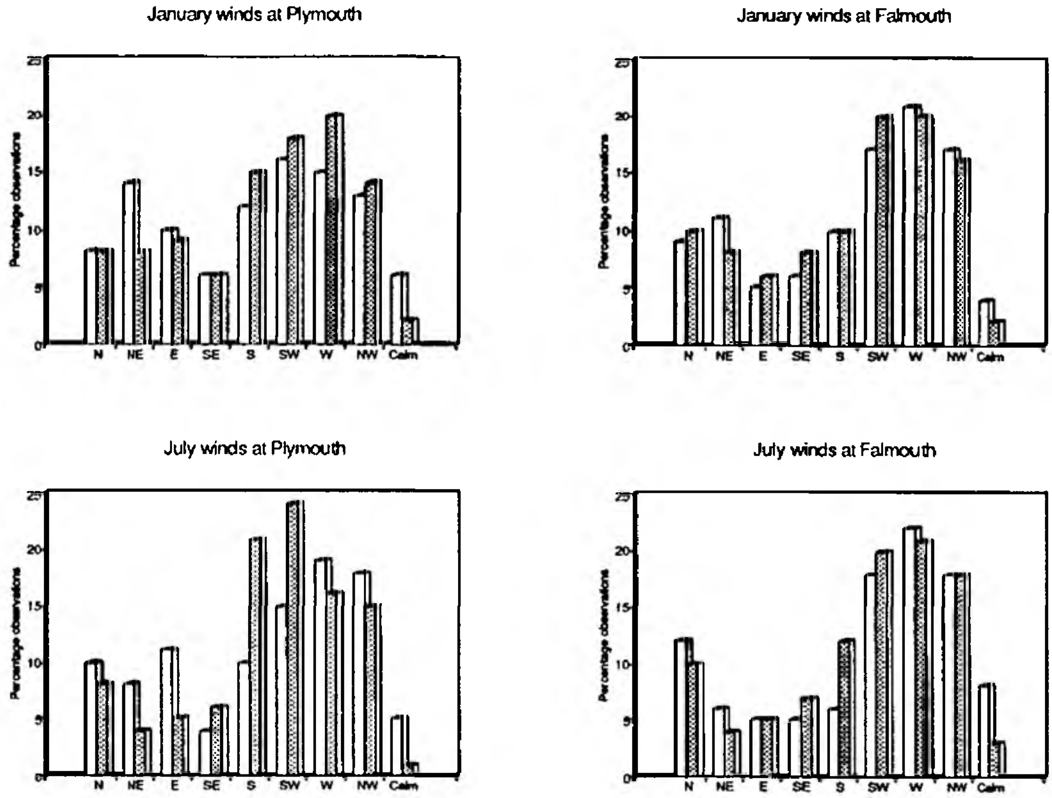


Figure 4. Climatic mean wind distribution in January and July at Falmouth and Plymouth, showing the percentage of winds from 8 directions. White bars are at 0900 h and shaded bars at 1500 h.

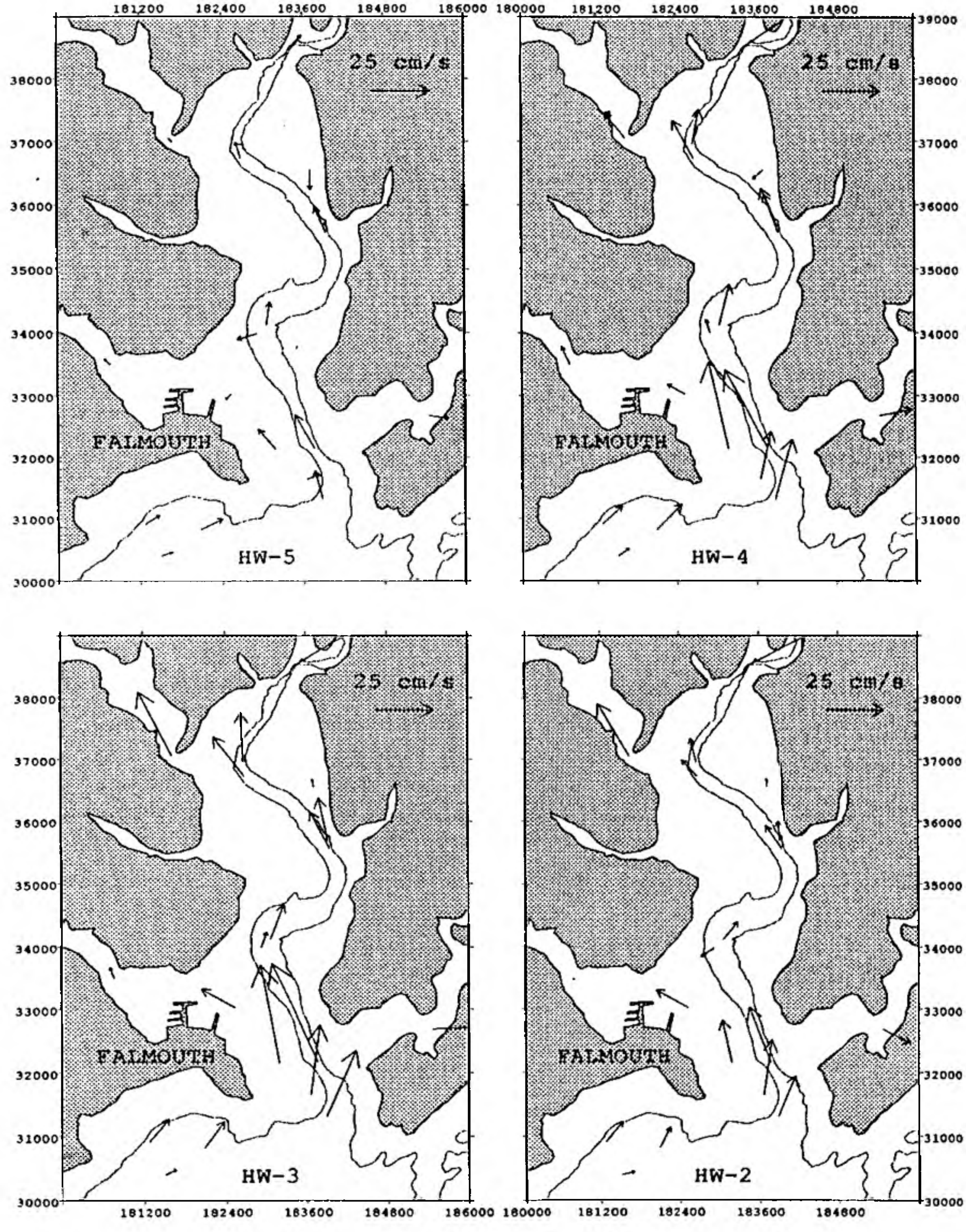


Figure 5. Mean range surface tidal currents at hourly intervals in Falmouth bay.

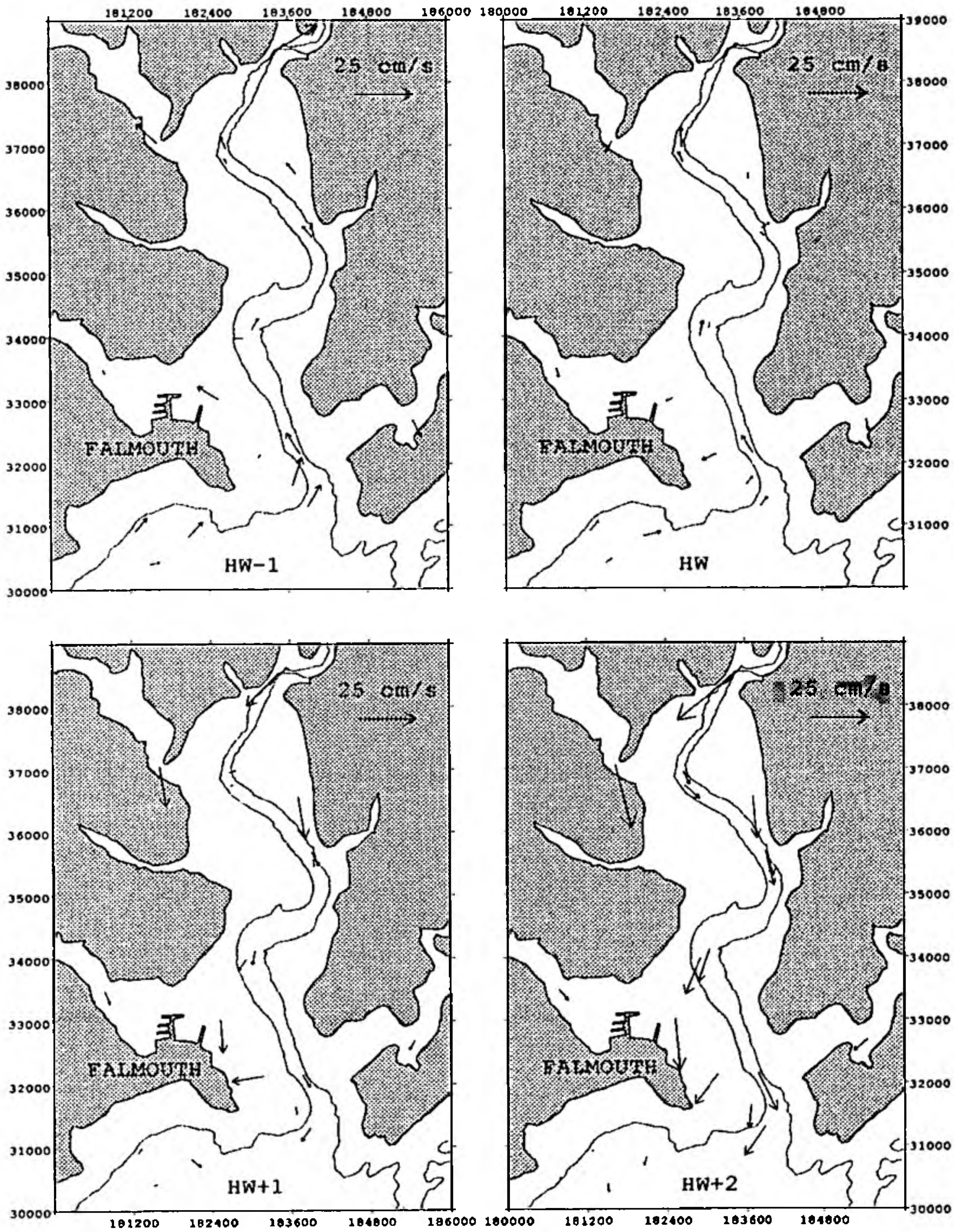


Figure 5. (cont)

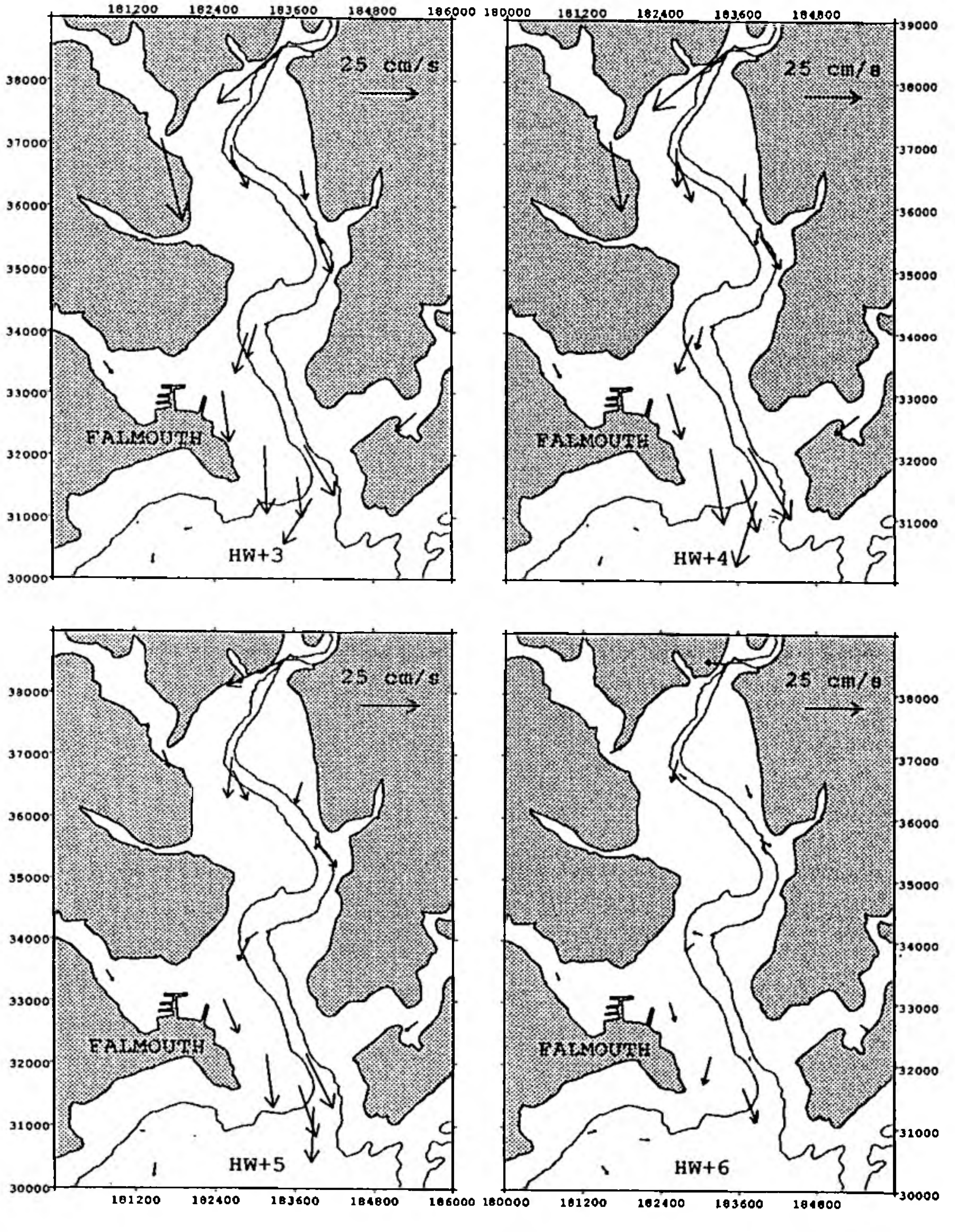


Figure 5. (cont)

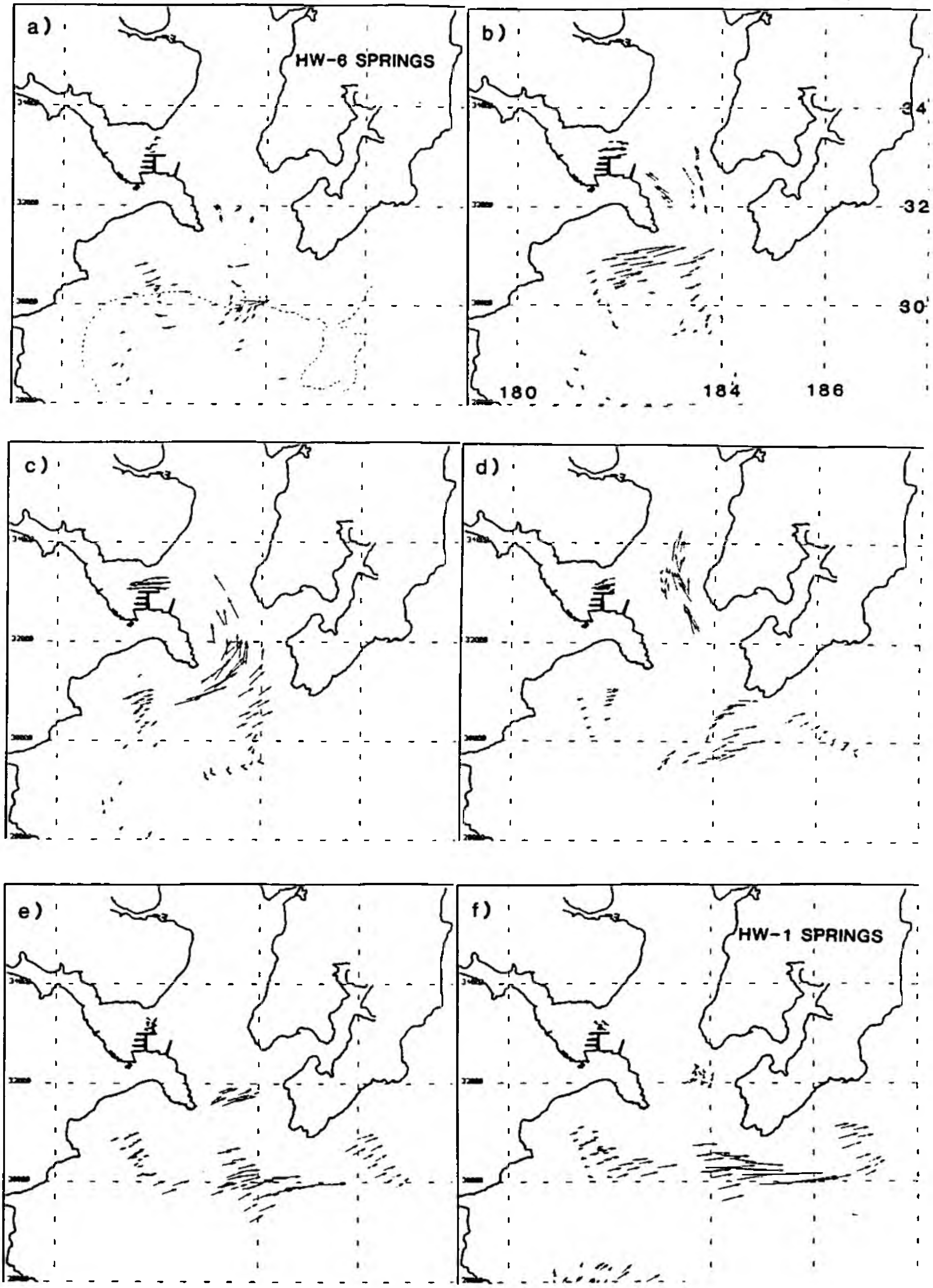


Figure 6. Spring tidal streams at hourly intervals in Falmouth Bay (from AH).

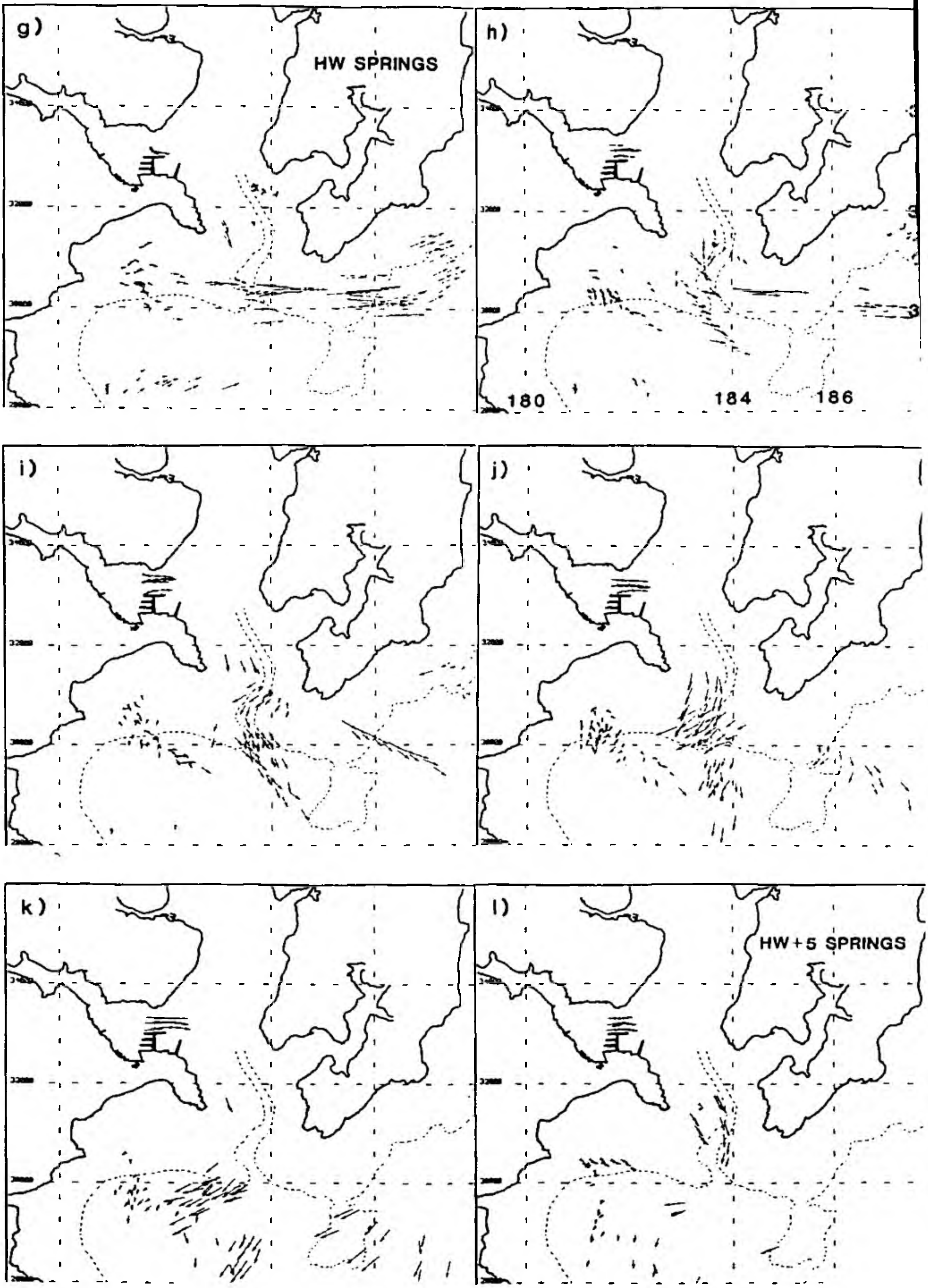


Figure 6. (cont)

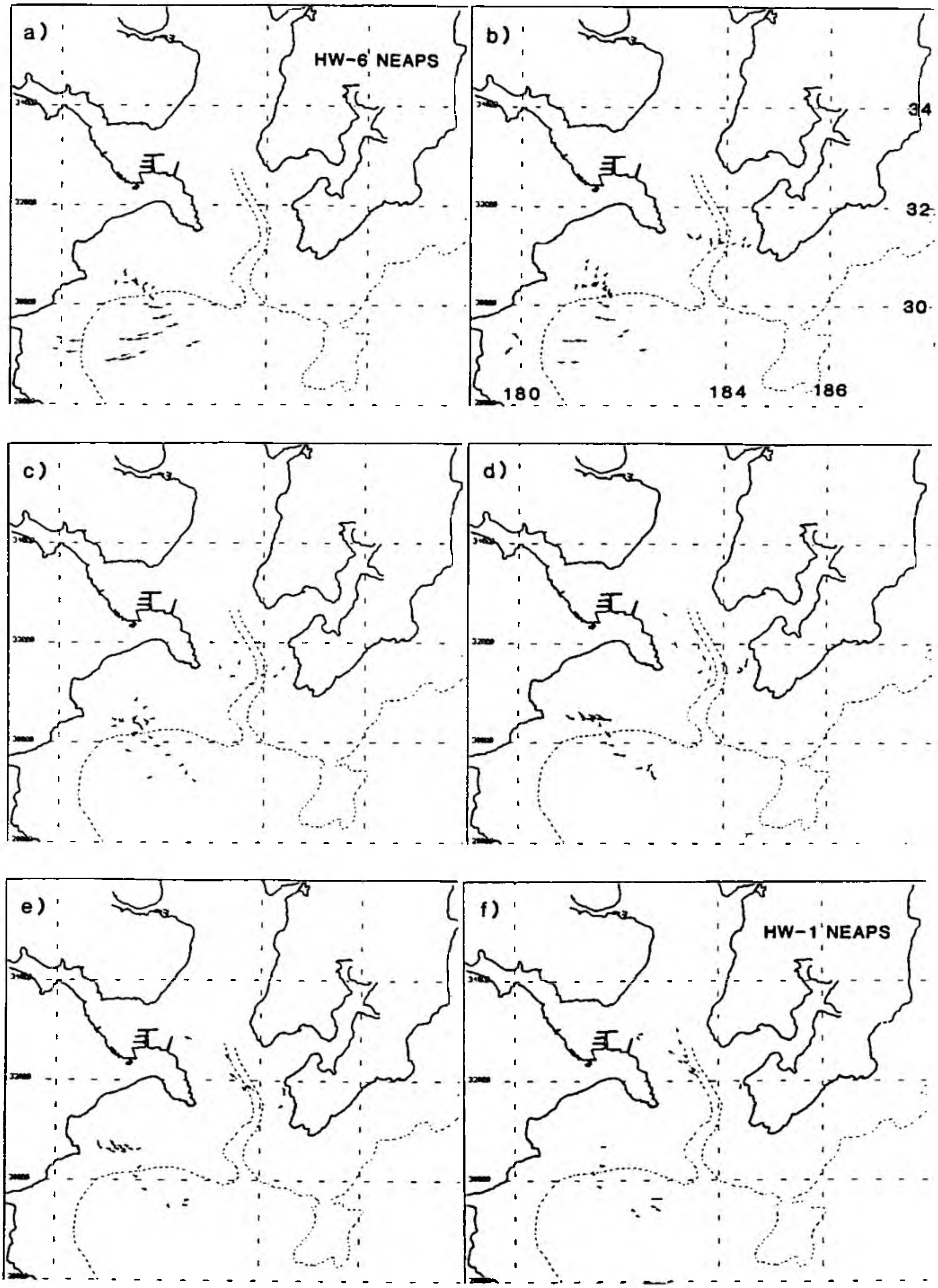


Figure 7. Neap tidal streams at hourly intervals in Falmouth Bay (from AH).

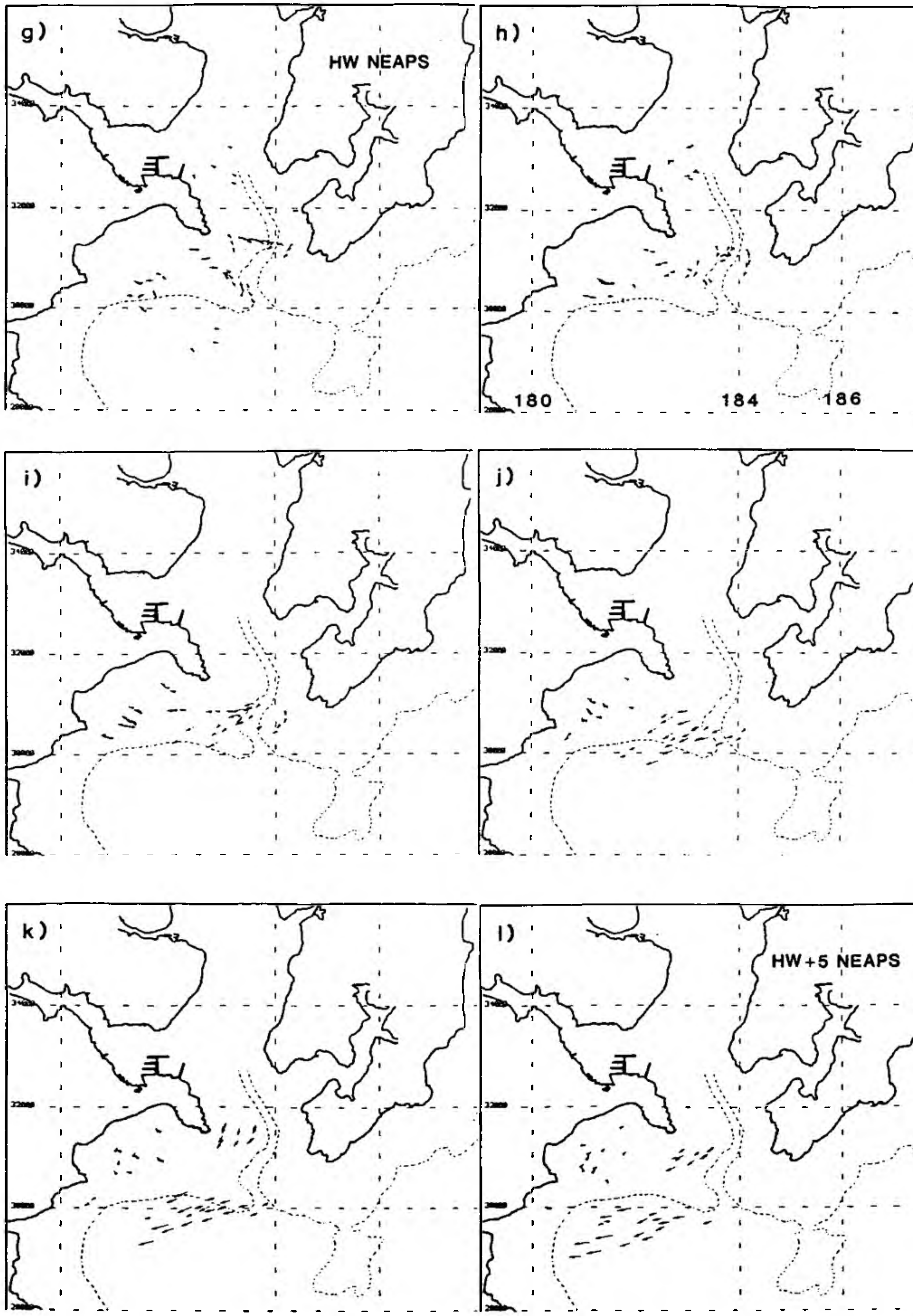
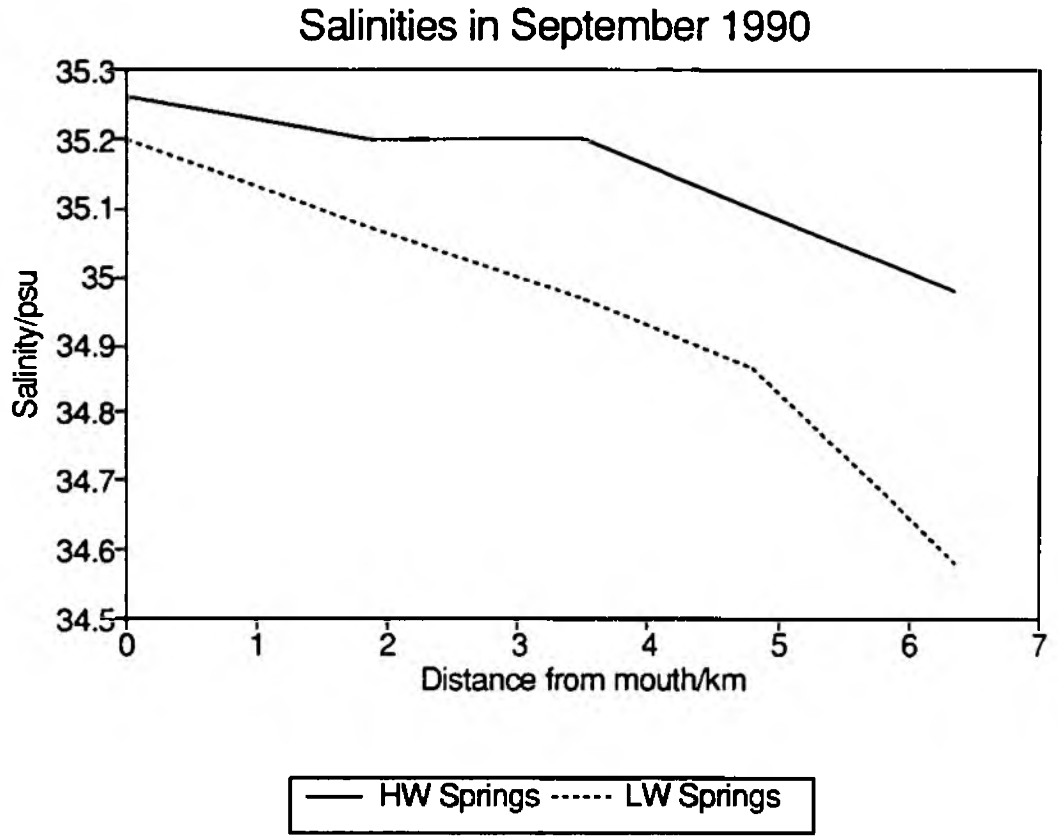


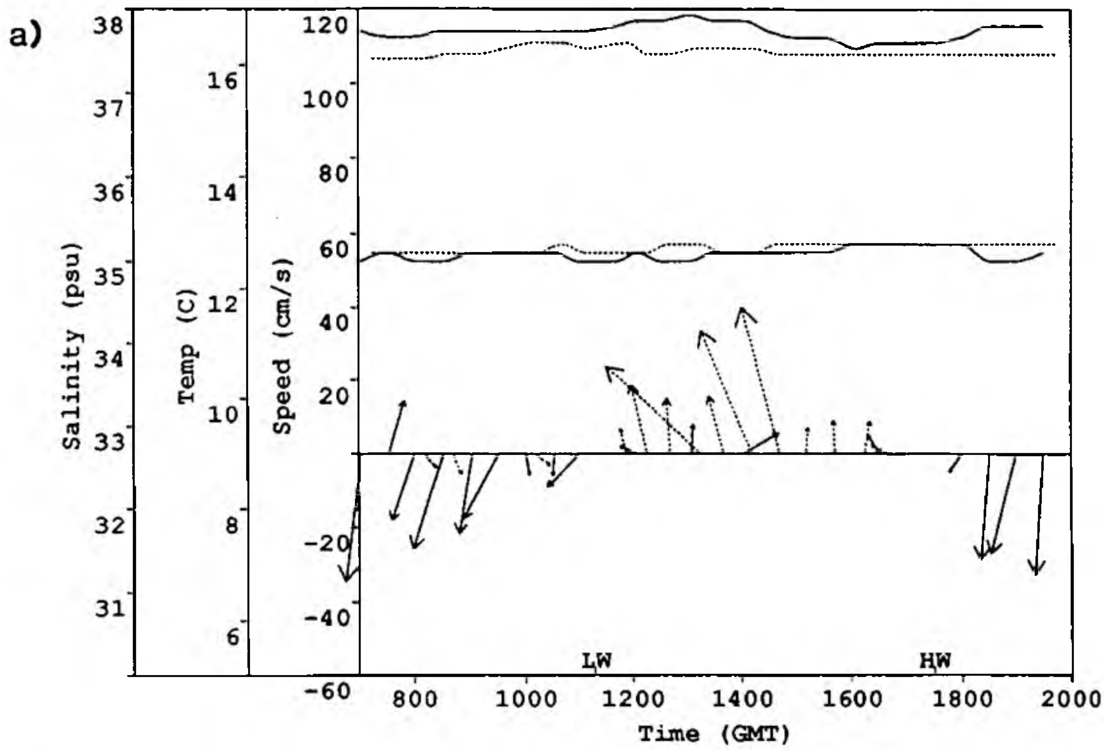
Figure 7. (cont)



Station	Date	Distance	HW	LW	Northing
2	8-Sep-90	0.00	35.26	35.20	32155
5	4-Sep-90	1.89	35.20	35.07	34046
6	5-Sep-90	3.52	35.20	34.97	35674
8	18-Sep-90	4.80	35.10	34.87	36955
10	19-Sep-90	6.36	34.98	34.58	38516
Mean			35.15	34.94	

Data for Falmouth Harbour from AH (1990)

Figure 8. Depth mean salinities at HW and LW (springs) along the axis of Falmouth Harbour in September 1990.



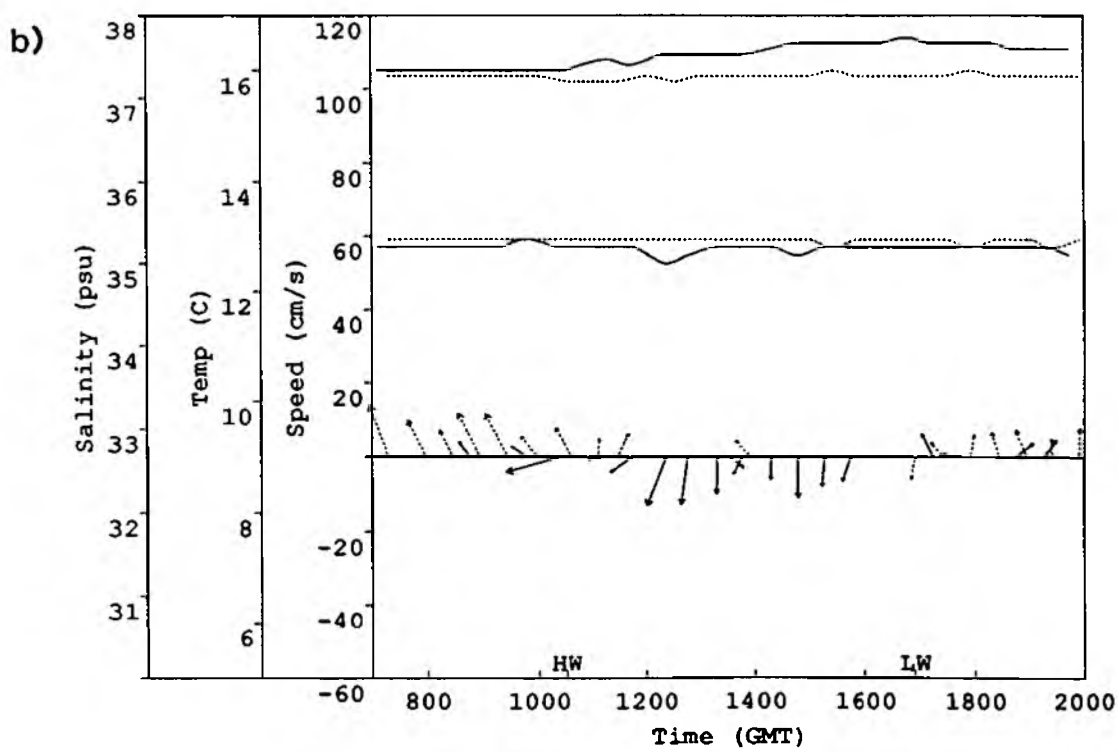


Figure 9. Velocity vectors, temperature and salinity measured at Sta. FS5 on a) spring tides and b) neap tides. Plain line is 0.5 m from the surface; dotted line is typically 1.5 to 2 m from the sea bed. The upper pair of lines are temperature and the lower pair salinity.

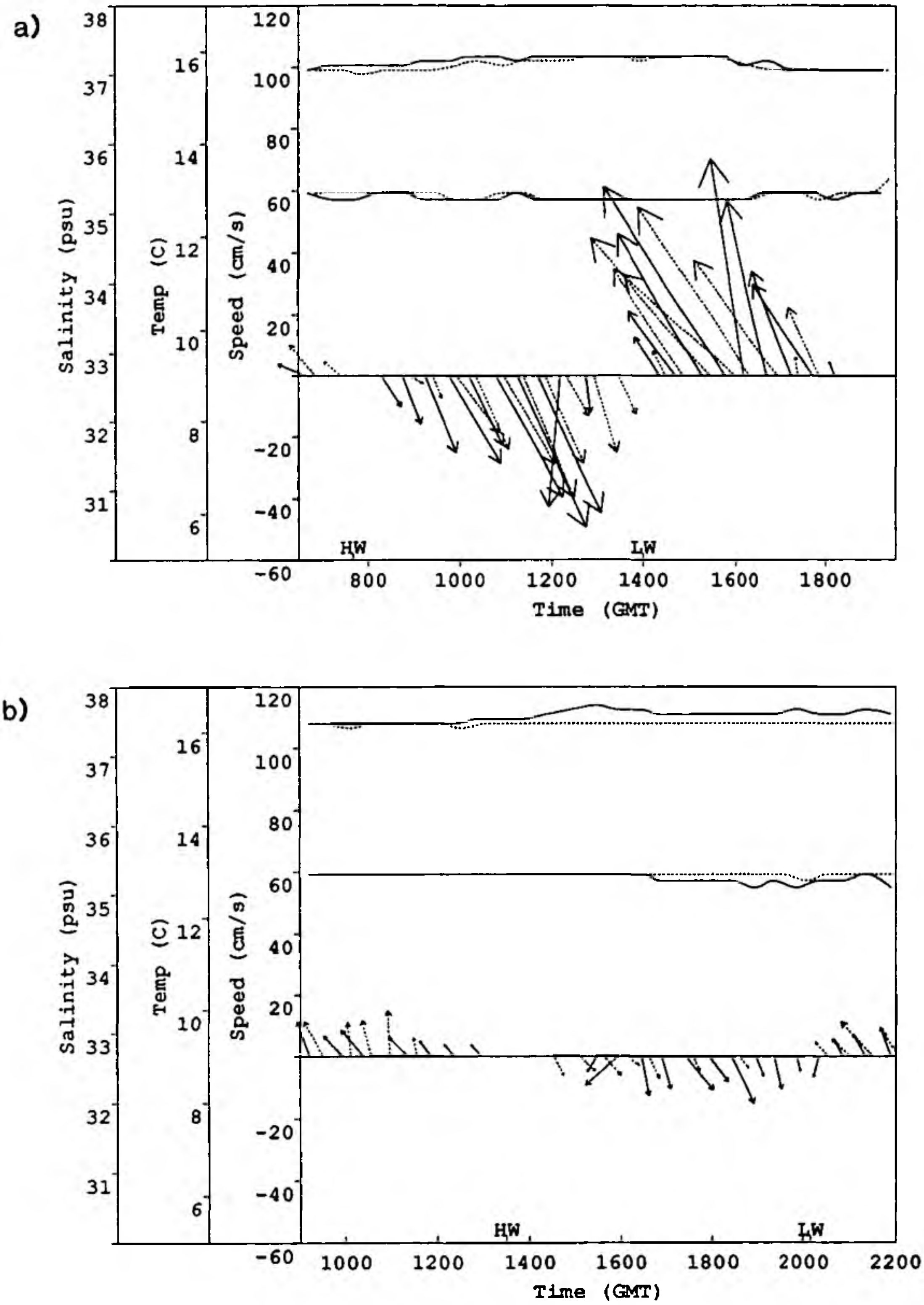


Figure 10. Velocity vectors, temperature and salinity measured at Sta. FS2 on a) spring tides and b) neap tides. (See caption for Fig. 9).

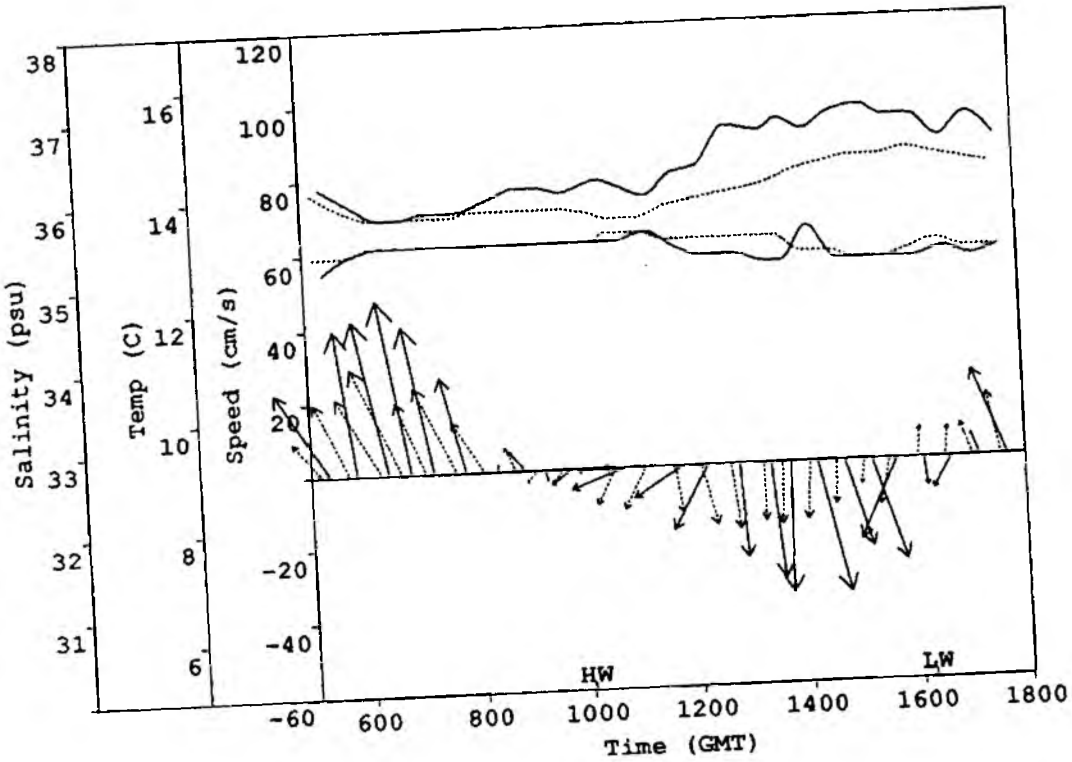


Figure 11. Velocity vectors, temperature and salinity measured at Sta. WE on neap tides. (See caption for Fig. 9).

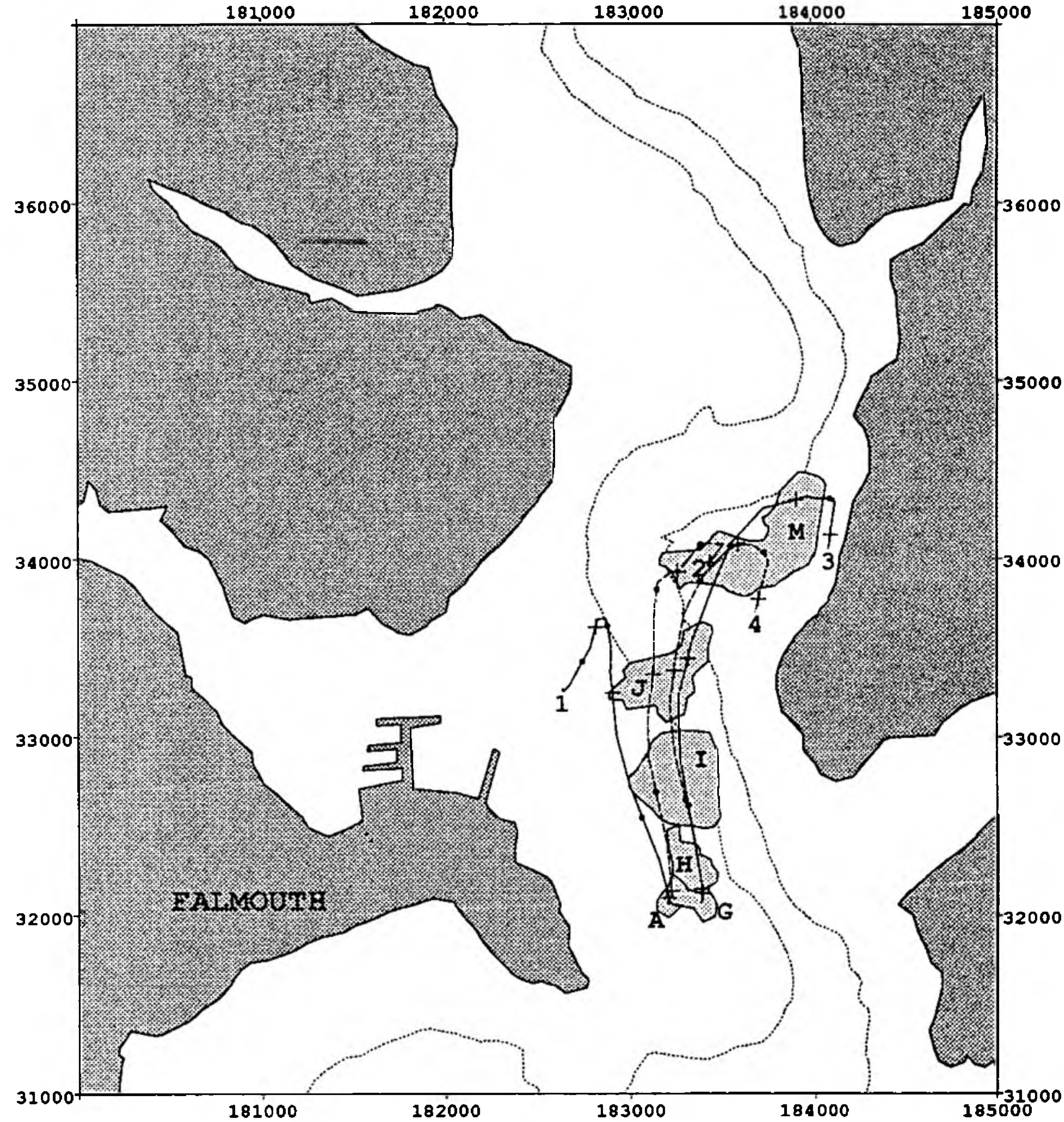


Figure 12. LW (neaps) drogue/float and dye tracks on 24th May 1992. See Table 5 for details. + marks drogue position at odd hours (e.g. 0900 h) and o is the position at even hours (e.g. 1000 h).

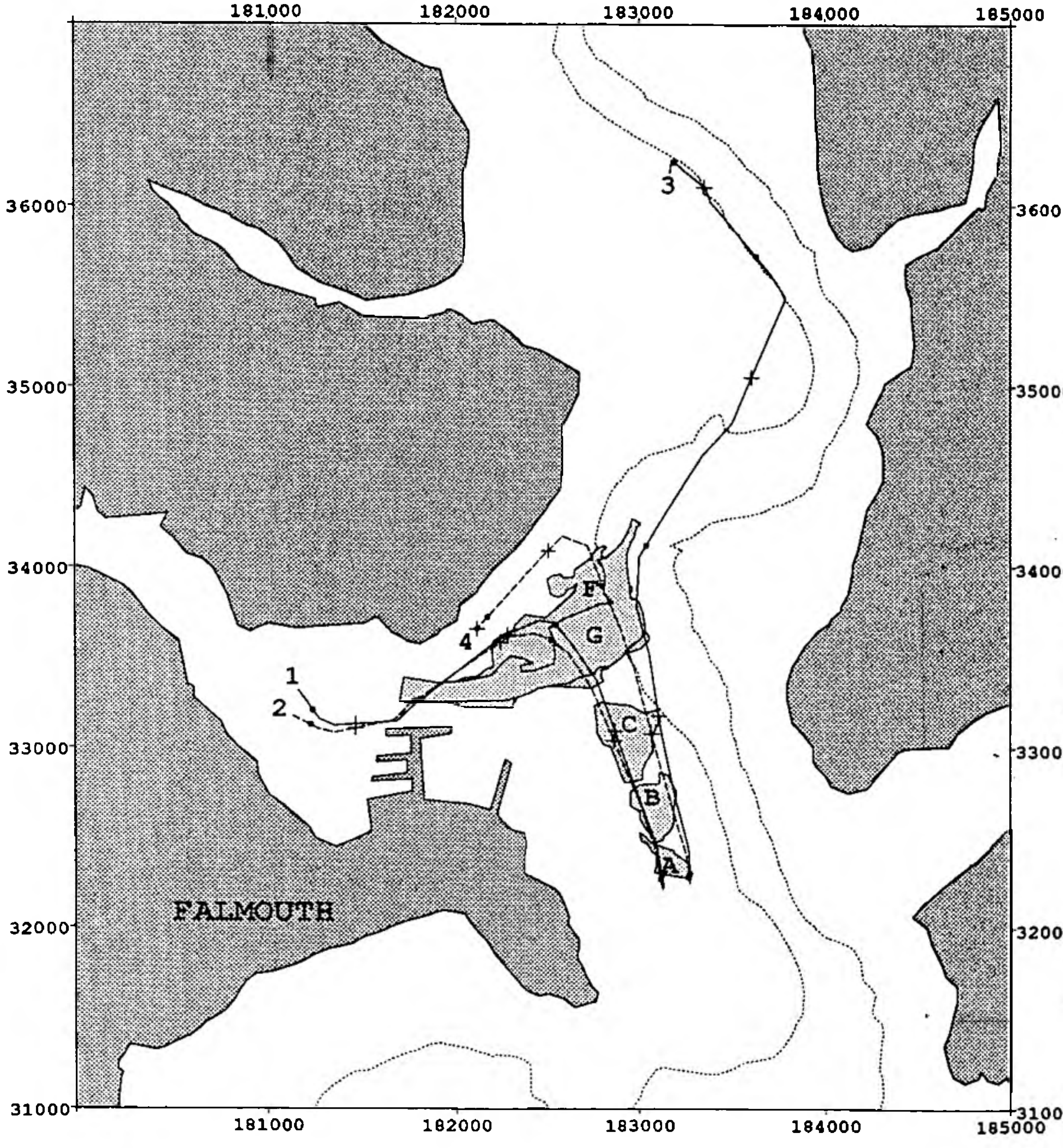


Figure 13. LW (Springs) drogue/float and dye tracks on 4th June 1992. (See caption for Fig. 12).

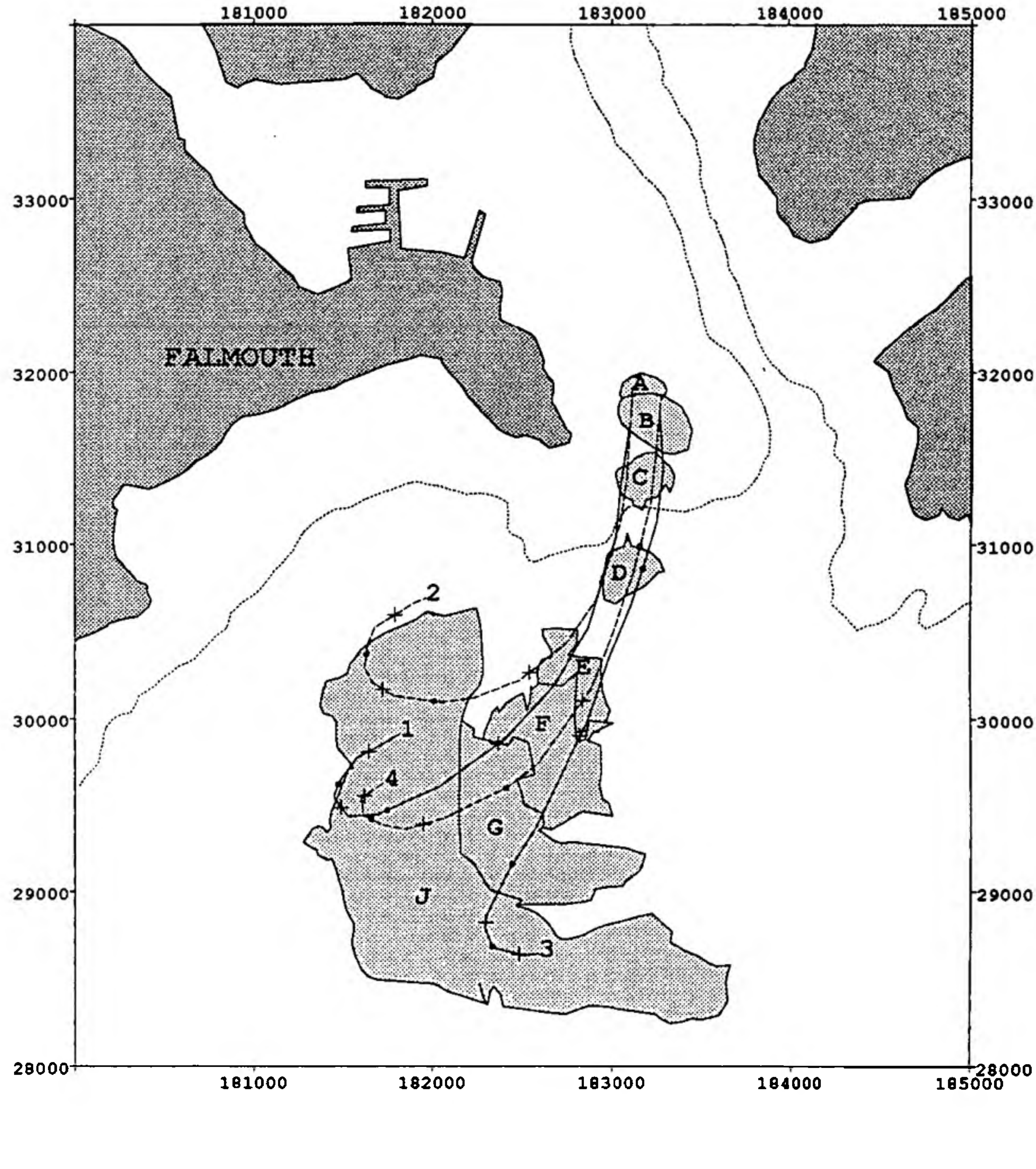


Figure 14. Mid-ebb (neaps) drogue/float and dye tracks on 28th May 1992. (See caption for Fig. 12)

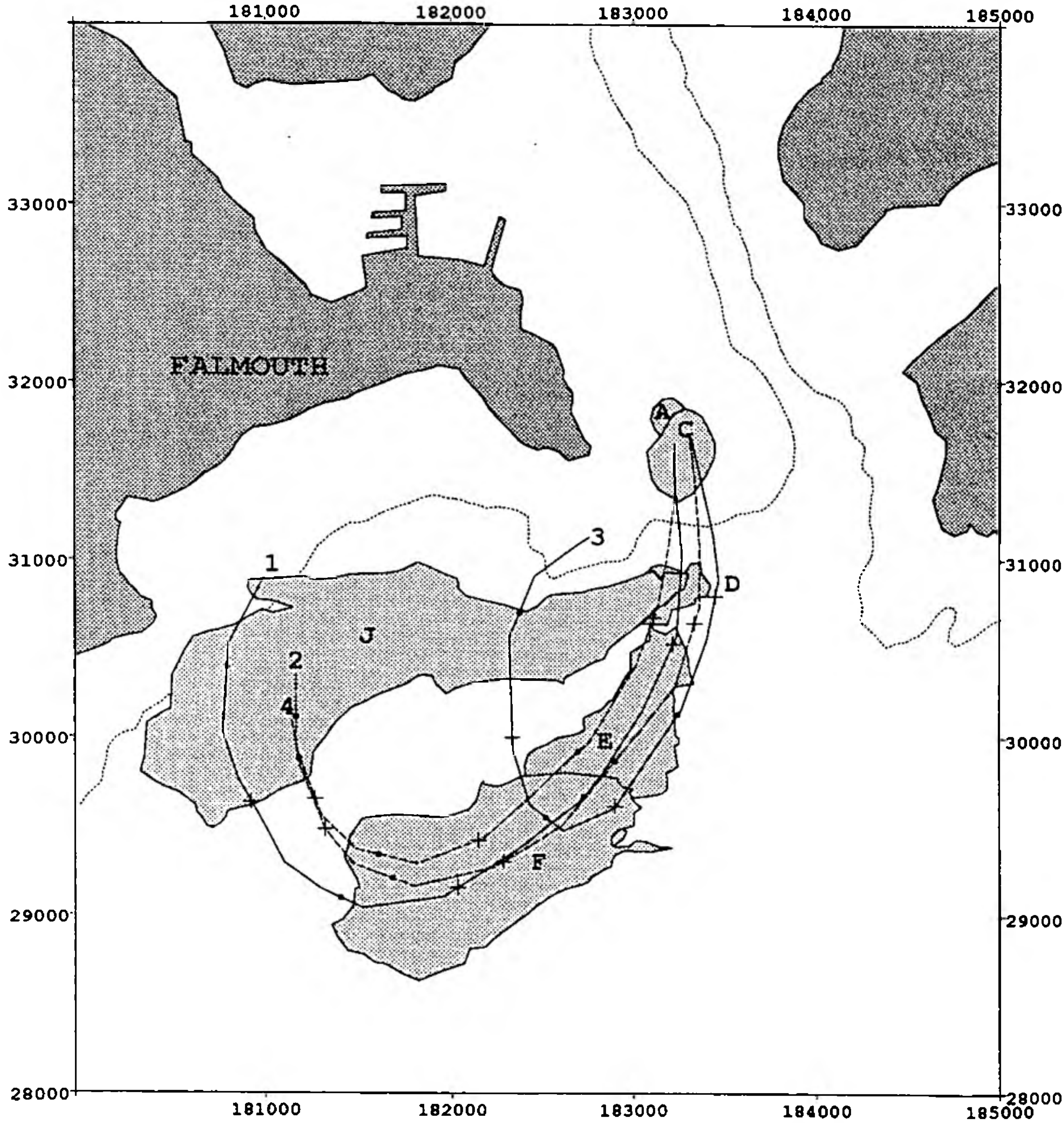


Figure 15. Mid-ebb (springs) drogue/float and dye tracks on 31st May 1992. (See caption for Fig. 12).

APPENDIX I - COMPUTATION OF VOLUMES IN FALMOUTH HARBOUR

The harbour and its entrance were divided up into 10 sections (Fig. A.1) and the area enclosed by HW, LW and 10 m lines in each section were measured using a digitizer. On Chart 32, HW corresponds to MHWS (5.3 m above CD, except in the highest reaches of the harbour near Truro) and LW to LAT (chart datum). The LW volume was computed, assuming a linear relationship between surface area and depth, as:

$$V_{LW} = \left(\frac{A_{LW} + A_{10}}{2}\right) \times 10 + \frac{A_{10} \times (D - 10)}{2}$$

where A_{LW} is the area at LW; A_{10} is the area enclosed by the 10 m contour; and D is the effective maximum depth of the deep water. If $D < 10$ m then

$$V_{LW} = \frac{A_{LW}}{2} \times D$$

The intertidal volume was calculated as

$$V_I = \left(\frac{A_{HW} + A_{LW}}{2}\right) \times ATR$$

where A_{HW} is the area at HW and ATR is the astronomical tidal range (5.9 m), and an assumption has been made that the surface areas of MHWS and HAT are the same. Finally, the HW volume of a section is given by

$$V_{HW} = V_{LW} + V_I.$$

The volumes for mean neap and mean spring tides, used to determine the cumulative volume curves, were calculated on the assumption that the intertidal volume is proportional to tidal range, and that the mean volume does not vary over the spring-neap cycle. For example, if the tidal range is r then the HW volume is

$$V_{HWr} = \left(\frac{V_{HW} + V_{LW}}{2}\right) + \left(\frac{V_{HW} - V_{LW}}{2}\right) \times \left(\frac{r}{5.9}\right)$$

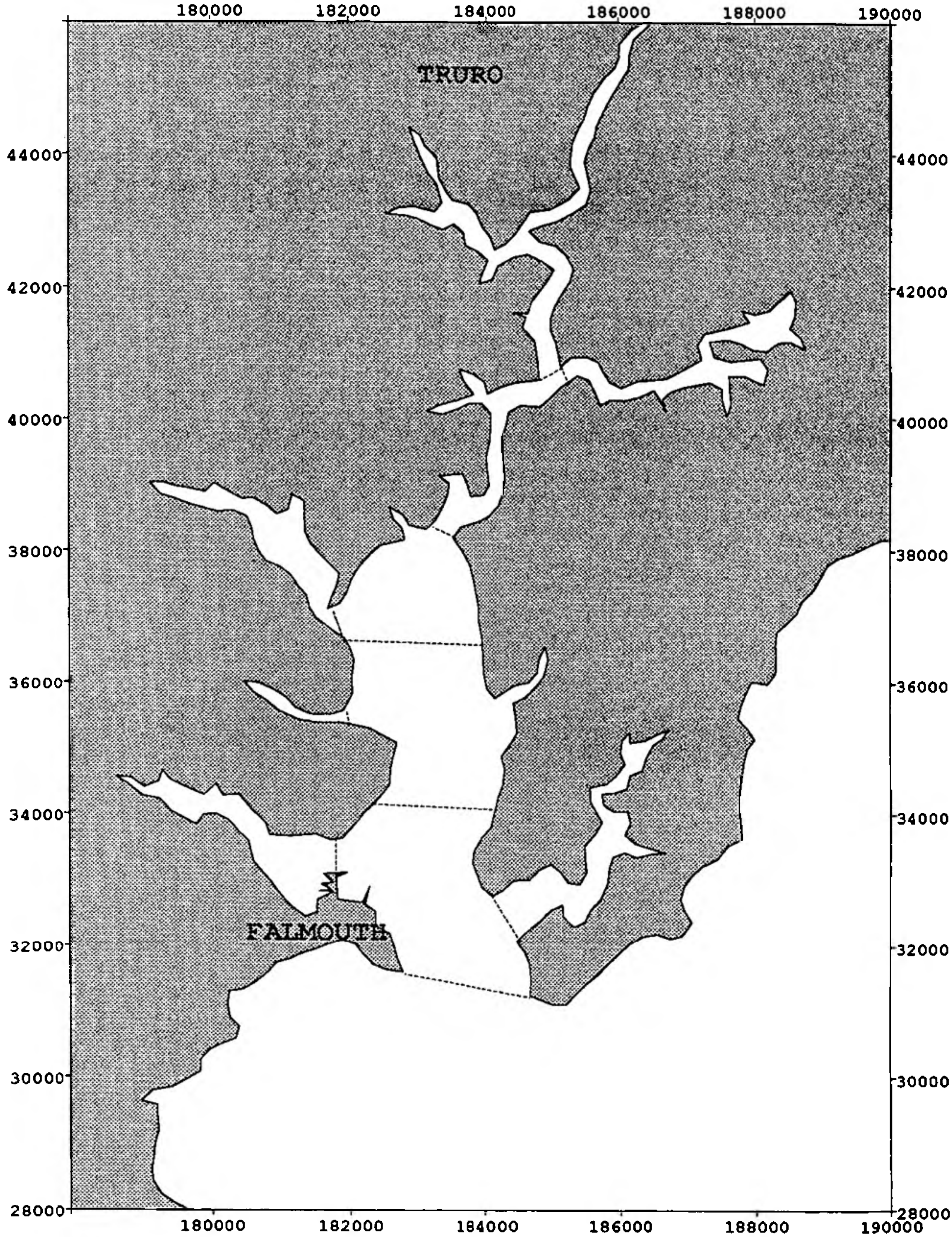


Figure A1. Division of harbour into segments for the purpose of computing cummulative volume curves.

APPENDIX II - ESTIMATES OF TOTAL FRESHWATER INFLOW

By P B Murray

An estimate of the daily freshwater inflow in to the Falmouth harbour system from 1st to 19th September 1990 was made based on the 10 freshwater riverine inputs identified by AH. Daily river flows, obtained at gauging stations by the NRA, were available for the rivers Kenwyn and Falmouth. AH measured a further six rivers on 6 days, spaced through September. For each of these rivers, the 6 measured flows were related to the values for the river Kenwyn, and a ratio was obtained. On dates without measurements, flows were estimated as a ratio of that for the Kenwyn. Finally, it was estimated that the sum of the catchment areas for the two rivers without any measurements (St Just Creek and Trethem Mill), was similar to that of the river at Penryn. The flows measured at Penryn were used as an estimate of the unmeasured rivers. The sum of the ten river flows provided the daily freshwater inflow.