AN OUTFALL SITING STUDY NEAR COCKSHOT POINT, WINDERMERE

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Introduction

In July 1985 members of staff from the Freshwater Biological Association met with representatives of the North West Water Authority to discuss the implications of relocating storm overflows in Windermere. It was explained that premature discharges from the existing storm overflows periodically give rise to public concern. The Authority therefore planned to replace the existing five overflows with one new overflow of improved quality. In the new scheme, storage tanks would be built on shore to reduce the frequency of discharge, and there would be some additional fine screening.

In May and September 1983 the Authority conducted a number of tracer experiments to identify the most appropriate site for the new outfall. A site just south of Cockshot Point was provisionally selected, but the experiments were all conducted during periods of north and north easterly winds, and there were no direct measurements of the currents at different depths. This study was commissioned to examine the pattern of water movement during southerly winds and to make more specific recommendations on the siting of the outfall. The local current structure in this relatively enclosed part of the lake is likely to be quite complex. It is possible that quite small changes in the position of the outfall could give rise to quite substantial differences in the pattern of effluent dispersion.

The recommendations in this report are based solely on considerations of physical transport. We do not have the necessary information to assess the ecological impact of the polluting load or comment on any health risks associated with the discharge.

The Cockshot Point Basin

For the purposes of this report the area south of Cockshot Point will be described as the Cockshot Point Basin.

Fig. 1 is a bathymetric map of this Basin and shows the location provisionally chosen for the outfall. The basin is 0.5 km^2 in area and has a mean depth of 5.2 m and a maximum depth of 16.2 m. It is bounded to the west by the privately owned Belle Isle, and to the east by public access land. A narrow channel ´C´ runs north from the basin into Bowness Bay, a number of boatyards and moorings surround the bay marked ´B´ on the map. The hypsographic curve in Fig. 2 shows that less than 15% of the basin area is more than 10 m deep. There is quite a deep ´pot´ in the centre of the basin but the total volume of water below the 10 m contour is only 4.0×10^5 m^3.

The temperature profiles in Fig. 3a demonstrate that the basin remains thermally stratified throughout the summer. The intensity of stratification is somewhat greater in the bay than in the more exposed North Basin (Fig. 3b). In the Cockshot Point Basin the relatively small volume of water below the thermocline regularly becomes anoxic in summer. Any additional organic loading will, of course, accentuate this oxygen demand, so it is important to disperse the effluent as efficiently as possible in the epilimnion.

Surface water movements around Cockshot Point

Preliminary observations on surface water movements around Cockshot Point were made using small (250 ml capacity) drift bottles. The bottles were numbered and released along transects perpendicular to the wind. Two drift bottle experiments were completed on successive days in October 1985. On both occasions

Fig. 1. A bathymetric map of the Cockshot Point Basin showing the position provisionally chosen for the outfall (♦). The channel into Bowness Bay is marked with the letter 'C', and the sensitive boatyard area with the letter 'B'. The depth contours are in metres.

Fig. 1

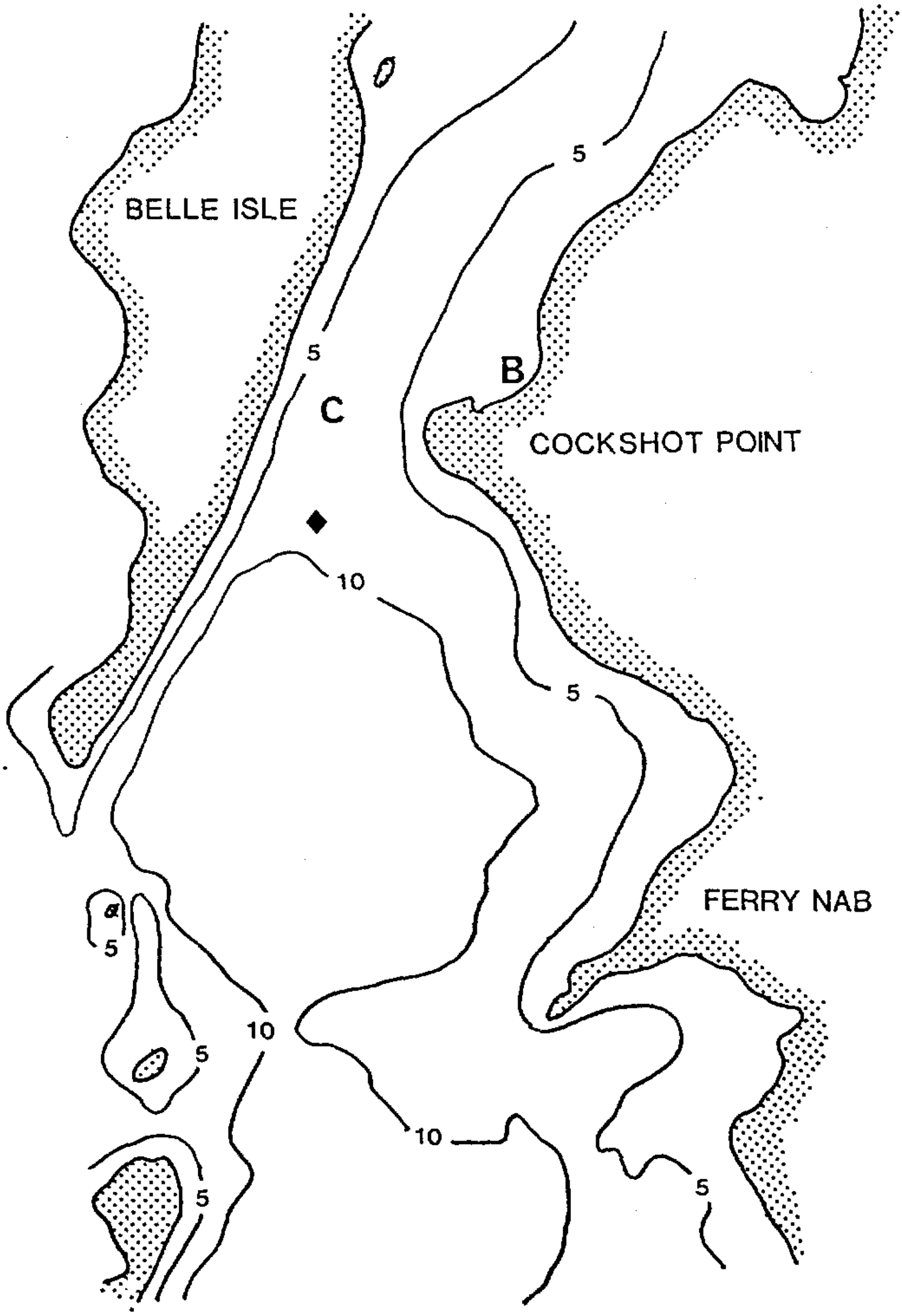


Fig. 2. A hypsographic (depth/area) curve for the Cockshot Point Basin.

Fig. 2

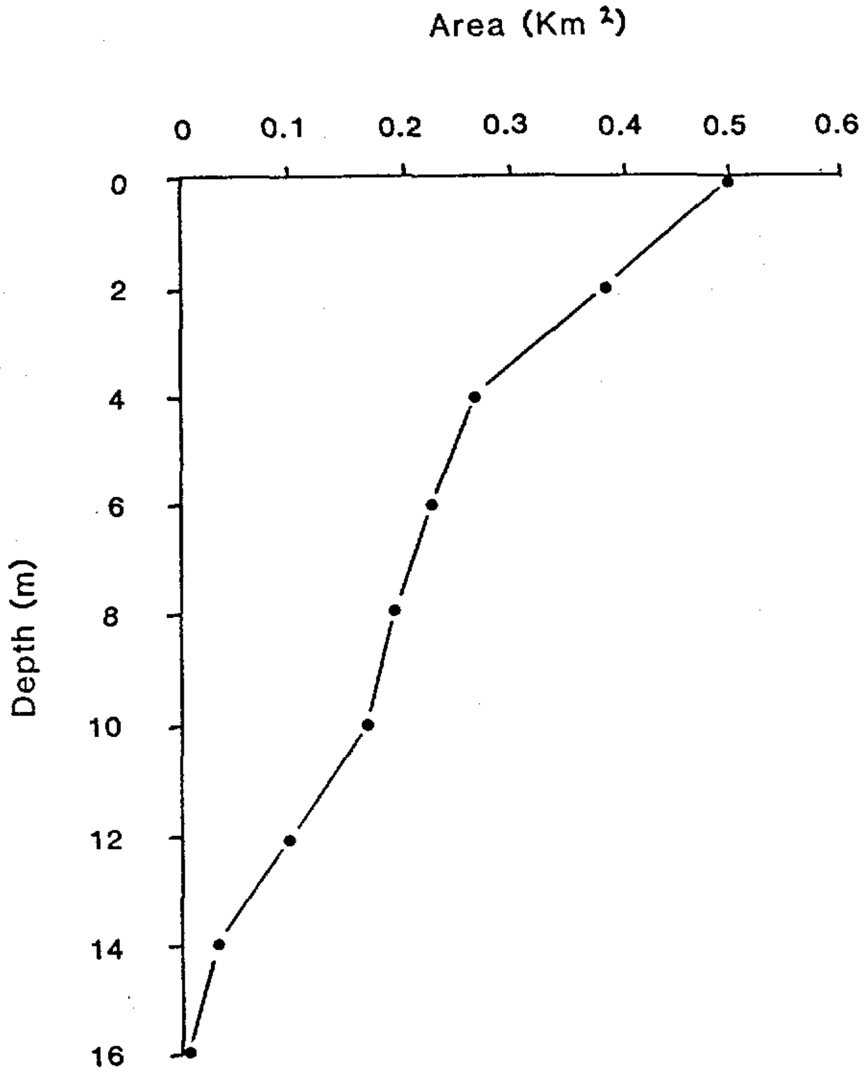
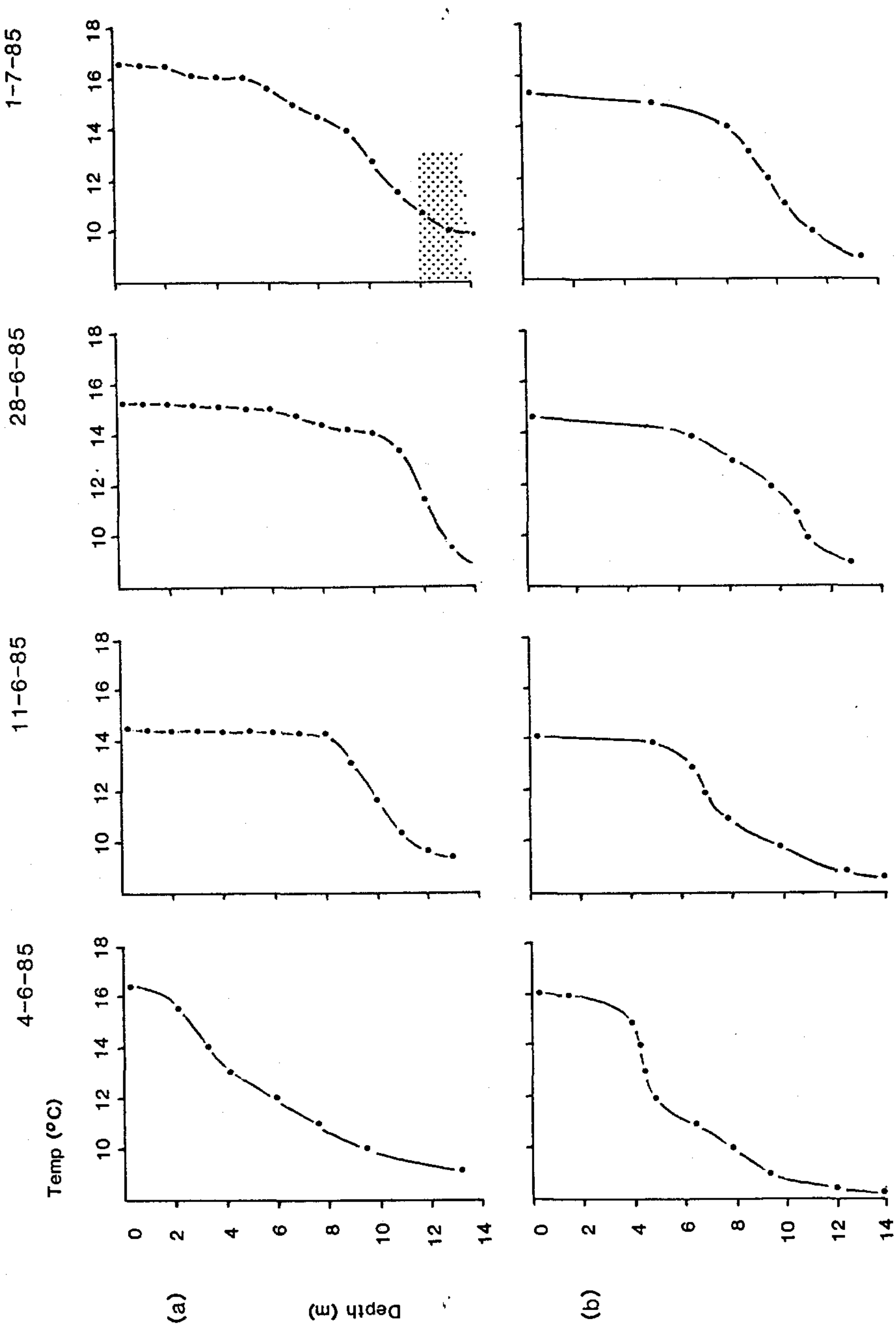


Fig. 3. A comparison of temperature profiles taken at a central location in the basin (a) with those taken at the North Basin buoy (b). The shaded area indicates that the hypolimnion has become anoxic.

Fig. 3



1-7-85
28-6-85
11-6-85
4-6-85
Temp (°C)
10
12
14
16
18
0
2
4
6
8
10
12
14
Depth (m)
(a)
(b)

the boat crew stayed near the bottles as they drifted downwind and so recovered over 80% of the bottles released.

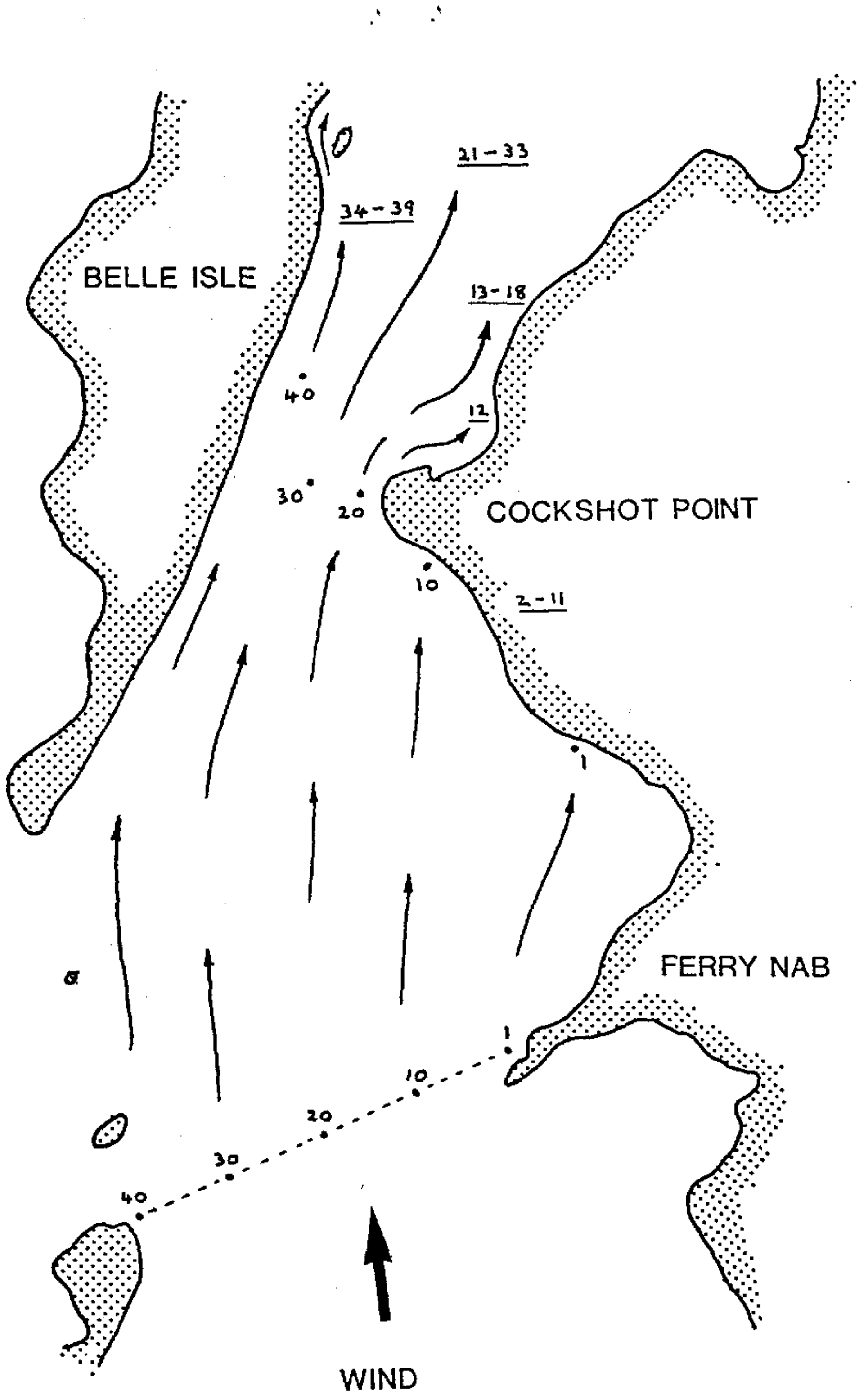
Fig. 4 shows the result of the drift bottle experiment conducted on the 3rd October when a moderate wind was blowing from the south. The bottles were released from the Windermere Ferry at 10.30 hours GMT and the positions of a few bottles recorded before they reached the shore. Within two hours bottles 1-11 had arrived on shore, and bottles 12-18 were being carried around Cockshot Point into the boatyard bay. Between 13.00 and 14.00 hours GMT the open water area to the north of Cockshot Point was searched for bottles. Bottles 21-33 were found moving north into Bowness Bay but bottles 34-39 had become trapped in a sheltered backwater on Belle Isle.

Fig. 5 shows the results of the drift bottle experiment conducted on the 4th October when the wind was blowing strongly from the south east. A large number of bottles released on a transect just south of Belle Isle drifted along the island and ended up in the sheltered backwater. Bottles 3-7 were recovered from Cockshot Point and only one bottle (No. 2) was carried around the headland into the boatyard bay. Between 12.00 and 13.00 hours GMT bottles 9-14 were found heading north and were later recovered just south of Rayrigg Meadows.

The results of the drift bottle experiments are encouraging in that they show a steady surface flow with no horizontal gyres or countercurrents in the bay. The pattern of movement out of the basin into Bowness Bay is, however, potentially troublesome since a proportion of the water moving northwards ends up in the sensitive boatyard region. The longshore drift along Belle Isle could also prove embarrassing if this deposited substantial amounts of particulate matter in the sheltered backwater.

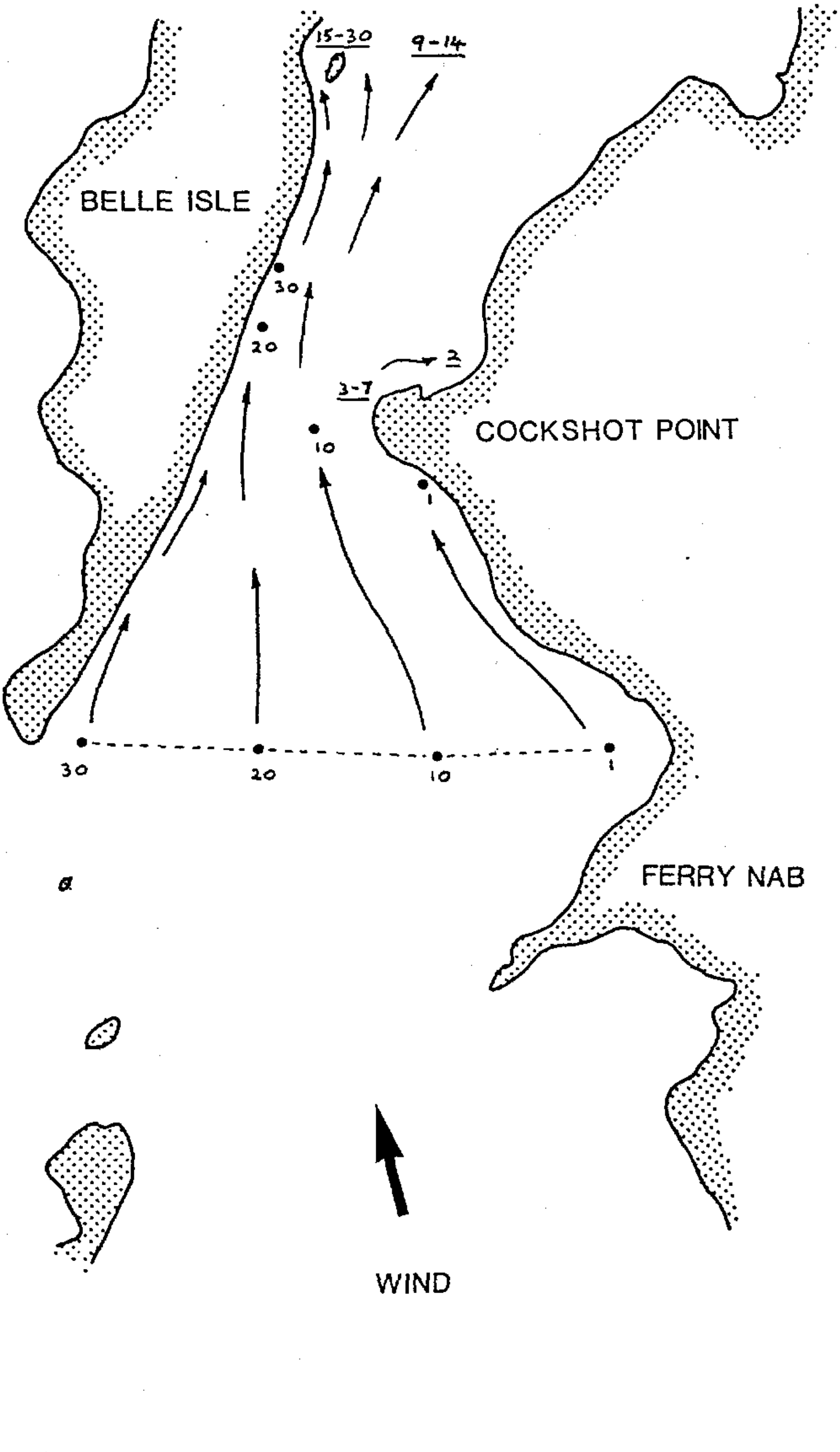
Fig. 4. The drift bottle experiment conducted on the 3rd October 1985. The numbered points show the position of selected bottles in open water. The underlined numbers show the position of the bottles on shore or at the point of recovery. The streamlines have been added to aid interpretation.

Fig. 4



BELLE ISLE
COCKSHOT POINT
FERRY NAB
WIND
34-39
21-33
13-18
12
2-11
40
30
20
10
1

Fig. 5. The drift bottle experiment conducted on the 4th October 1985. Notation as in Fig. 4


15-30
9-14
BELLE ISLE
30
20
3-7
2
COCKSHOT POINT
10
1
30
20
10
1
FERRY NAB
a
WIND

The efficiency of wave-mixing around Cockshot Point

When a reasonably strong wind blows over a lake waves form and transfer momentum to deeper layers. The efficiency of mixing near the surface is strongly influenced by wave action, so it is of interest to examine the spatial variation in the depth of wave-mixing. The depth of the wave-mixed layer is usually considered to be half the wavelength (Smith and Sinclair 1972). In deep water the wavelength can be estimated from:

$$\lambda = 1.56\ T^2$$

where T^2 is the wave period calculated from the wave prediction technique developed by the Beach Erosion Board (U.S. Army, 1962):

$$gT/W = 0.46\ [gF/w^2]^{0.28}$$

In this equation w is the mean wind speed, g the acceleration due to gravity, and F the effective fetch for a particular location. The fetch is not the greatest straight line distance over water but is calculated as a weighted mean of several radial measurements (Beach Erosion Board 1962).

Figs 6 and 7 show the results of calculating the depth of the wave-mixed layer at several locations around Cockshot Point. Fig. 6 shows the estimates for a wind speed of 5 m s^{-1} and Fig. 7 the corresponding estimates for a wind speed of 10 m s^{-1}. In both cases the wind was considered to blow from the south and the wavelength taken to be unaffected by the depth of water. The figures show the strong sheltering effect of Cockshot Point, and highlight the areas of still water north of this headland. These results suggest that wave action will generaly have little effect on the transportation of pollutants in the Cockshot Point Basin. With strong winds there may be some local entrainment, but by then the general mixing process will be at its most intense.

Fig. 6. The depth of wave-mixing (m) around Cockshot Point when a 5 m s^{-1} wind blows from the south.

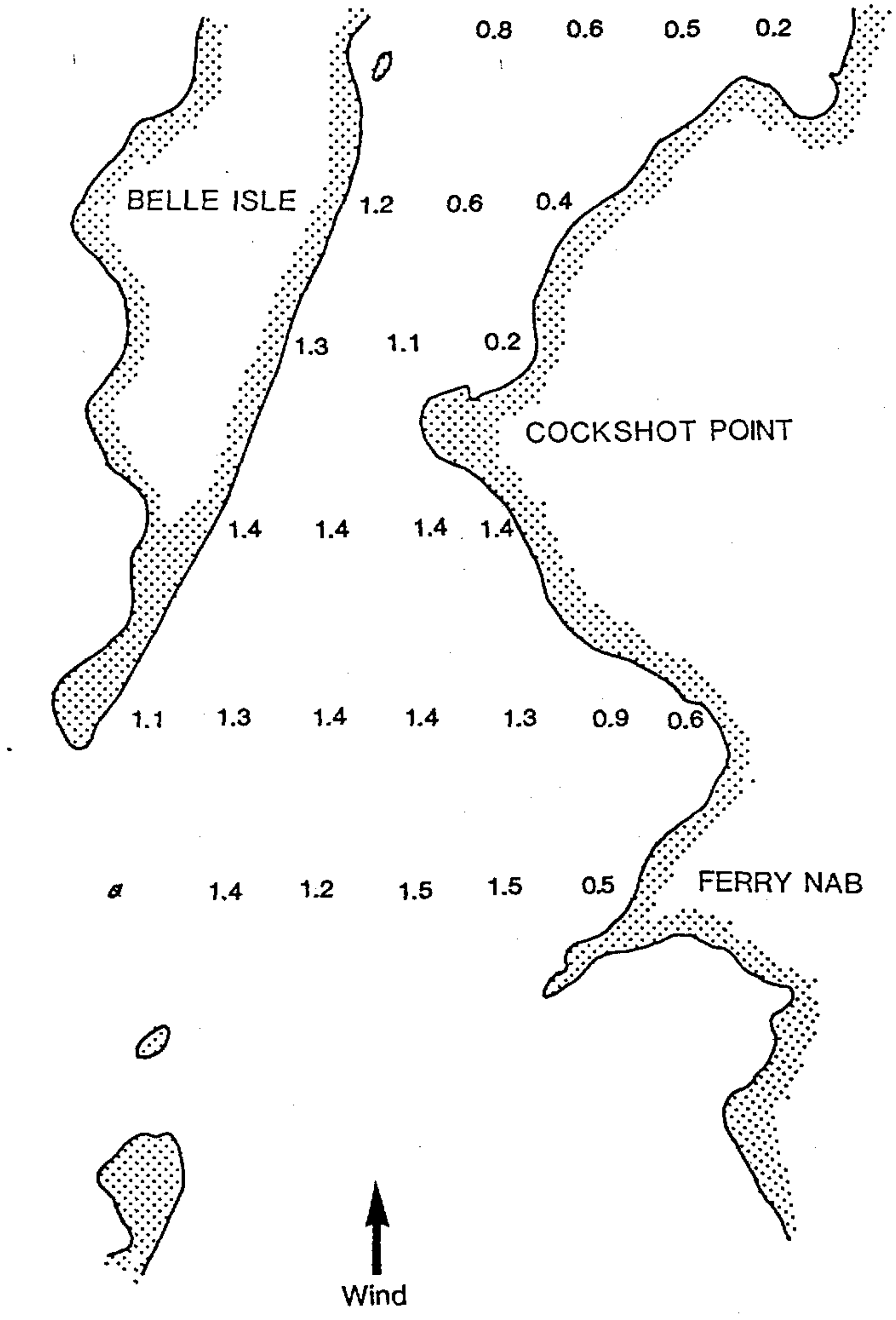
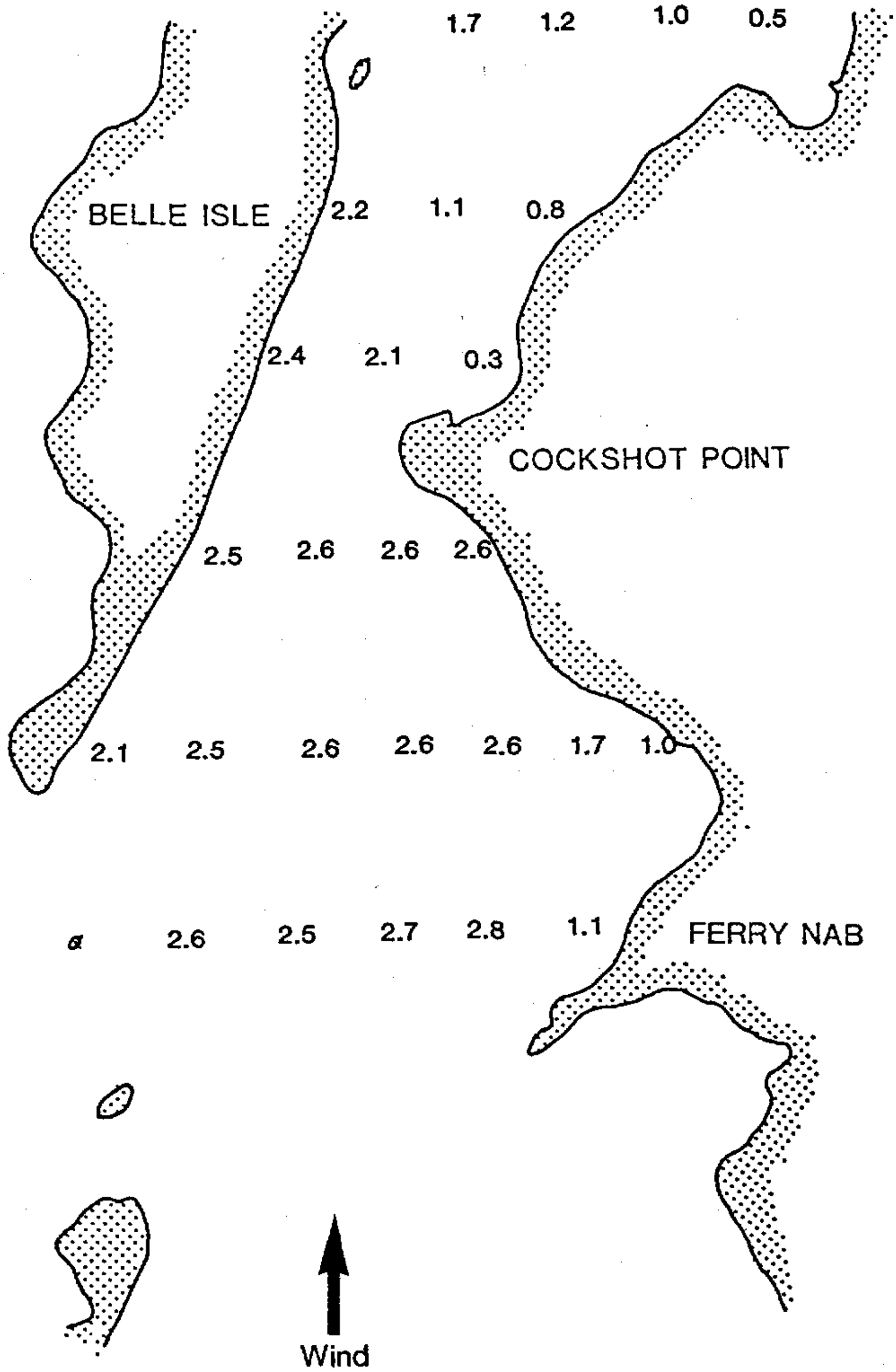

0.8
0.6
0.5
0.2
BELLE ISLE
1.2
0.6
0.4
1.3
1.1
0.2
COCKSHOT POINT
1.4
1.4
1.4
1.4
1.1
1.3
1.4
1.4
1.3
0.9
0.6
1.4
1.2
1.5
1.5
0.5
FERRY NAB
Wind

Fig. 7. The depth of wave mixing (m) around Cockshot Point when a 10 m s^{-1} wind blows from the south.


1.7
1.2
1.0
0.5
BELLE ISLE
2.2
1.1
0.8
2.4
2.1
0.3
COCKSHOT POINT
2.5
2.6
2.6
2.6
2.1
2.5
2.6
2.6
2.6
1.7
1.0
2.6
2.5
2.7
2.8
1.1
FERRY NAB
Wind

The characteristics of the storm water discharge

To minimise the risk of surface entrainment it is clearly desirable to discharge the storm water in fairly deep water. Rainwater is usually only a degree or so cooler than ambient, so it is reasonable to assume that any storm water discharged at depth will form an identifiable plume that will rise to the surface. Strictly speaking a plume is an inflow possessing buoyancy but no momentum. In this report the word plume will be used loosely to describe the nature of the discharge even though the initial flow may possess some momentum. Such a buoyant plume can form an effective mechanism of disperson, but much will depend on the design and siting of the outfall. Near the point of discharge the diluting characteristics of the plume will be controlled primarily by the velocity distribution in the supply pipe. Further afield the behaviour of the plume will be influenced by the nature of the surrounding flow field, and in particular the vertical variations in the wind-driven current.

Vertical variations in the wind-driven current

George (1981) demonstrated that Coriolis effects give rise to appreciable rotations of the wind-driven current with depth in the South Basin of Windermere. In a confined area, like that south of Cockshot Point, such rotations will be distorted by boundary effects so there may be appreciable spatial variations in the form of the velocity profile. We used free-running depth specific drogues of the type described by George (1981) to measure these vertical and horizontal variations in current speed and direction. After some preliminary trials we chose three sites for our routine measurements : a site (A) in open water, a site (B) further into the bay and a site (C) north of the provisional outfall location. At each site drogues were released to float at 2 m depth intervals in the water column and allowed to drift away from a fixed marker. The direction of movement of each drogue was determined at intervals using a hand-held compass and the distance travelled measured by a split-image rangefinder. Some typical examples of the current trajectories observed during periods of south and south-westerly winds are presented in Figs 8 and 9. At the open water site (A) an Ekman type transport develops where the drift currents rotate progressively to the right of the wind (Ekman 1905). The mid-water currents then run across the lake from west to east and the deep return currents flow directly into the wind. At the inshore site (B) the Coriolis deflection to the right is constrained by the boundary and the deep water vectors point away from the shore. The flow patterns at site C, just north of the proposed location for the outfall proved highly variable. On some occasions there was a rapid northward transport near the surface, but on other occasions the surface current ran across the lake from east to west. On several occasions when we set the drogues further south we recorded very little movement at any depth. This suggests that we were in an area of converging currents and had positioned the drogues in a downwelling on the steep northern slopes of the basin.

Figs 10, 11 and 12 show some typical velocity profiles for sites A, B and C. These profiles have been obtained from the raw flow diagams by projecting the current vectors on planes running along and across the wind axis. At site A (Fig. 10) the drift and the return currents are frequently in balance both along and across the wind axis. At site B (Fig. 11) the drift current is countered by a return current that tends to flow to the left of the wind. This means that any effluent discharged at

Fig. 8. Drogue trajectories at three sites in the Cockshot Point Basin when the wind was blowing from the south-west. The length of the arrows is proportional to current speed, and the numbers show the depth of the drogues in metres.

Fig. 8

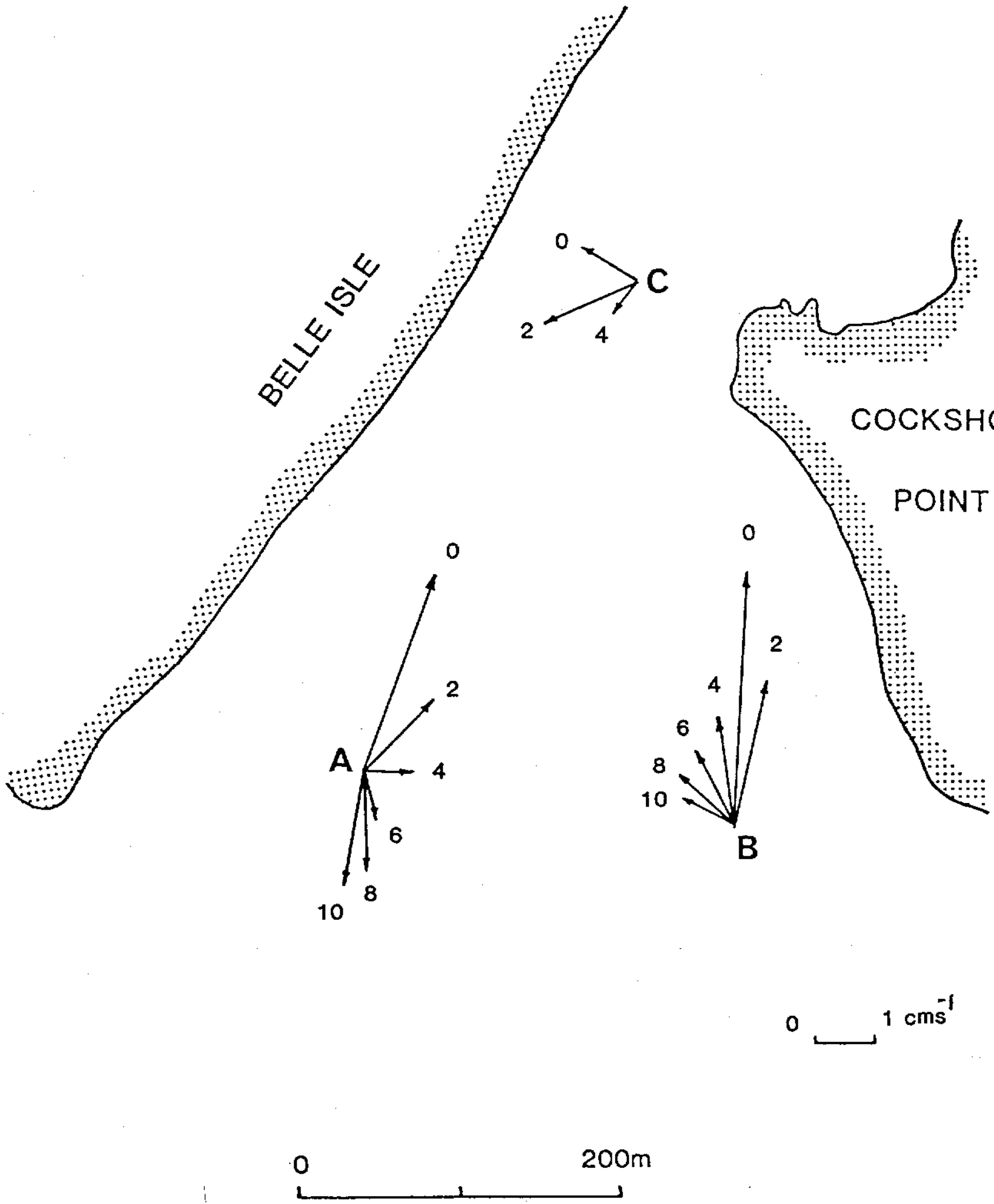

BELLE ISLE
COCKSHOT
POINT
0
C
2
4
0
2
A
4
6
10
8
0
2
4
6
8
10
B
0
1 cms⁻¹
0
200m

Fig. 9. Drogue trajectories at three sites in the Cockshot Point Basin when the wind was blowing from the south. Notation as in Fig. 8.

Fig. 9

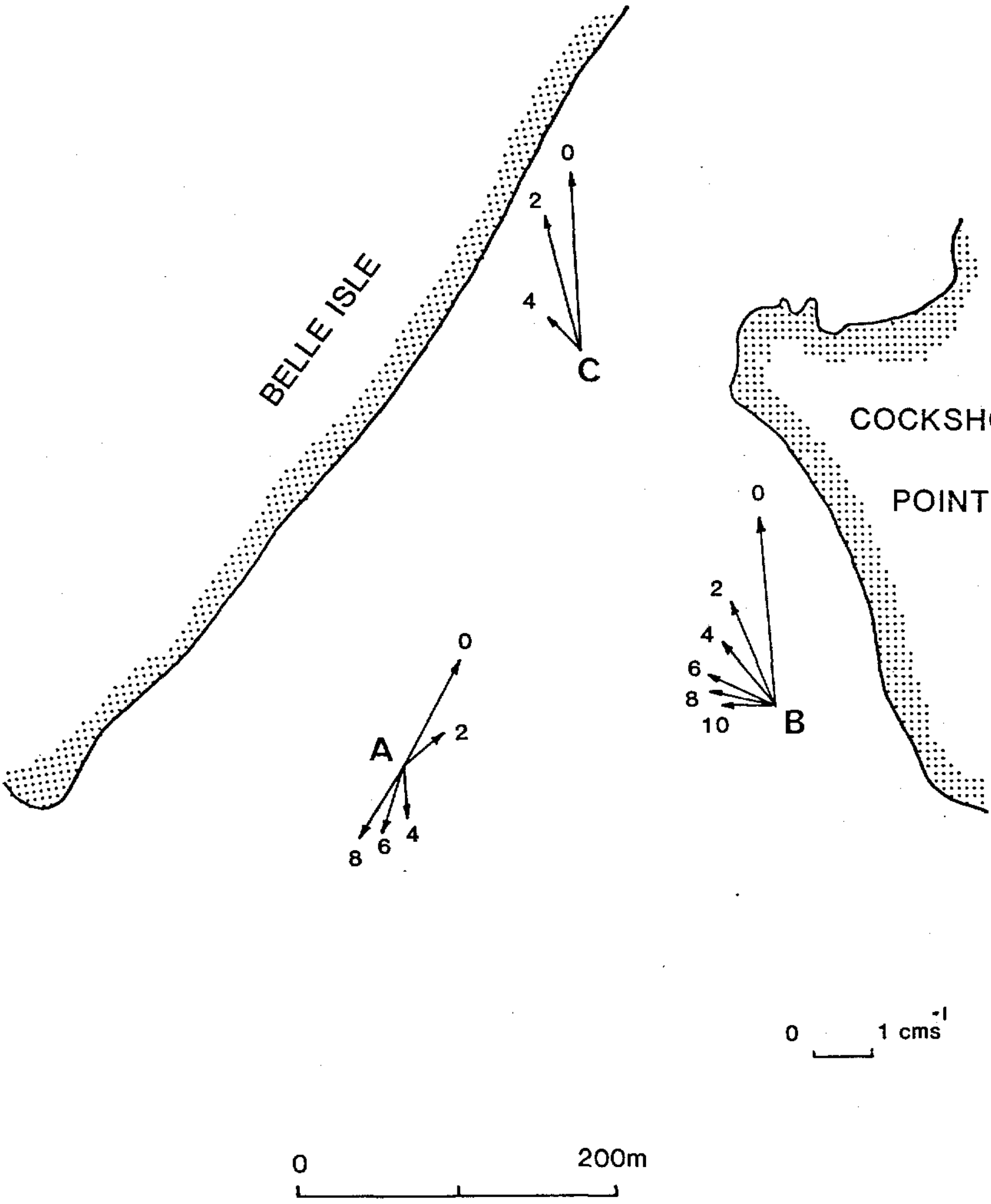


Fig. 10. Representative velocity profiles at site A. (a) 12 December 1985 (b) 20 December 1985.

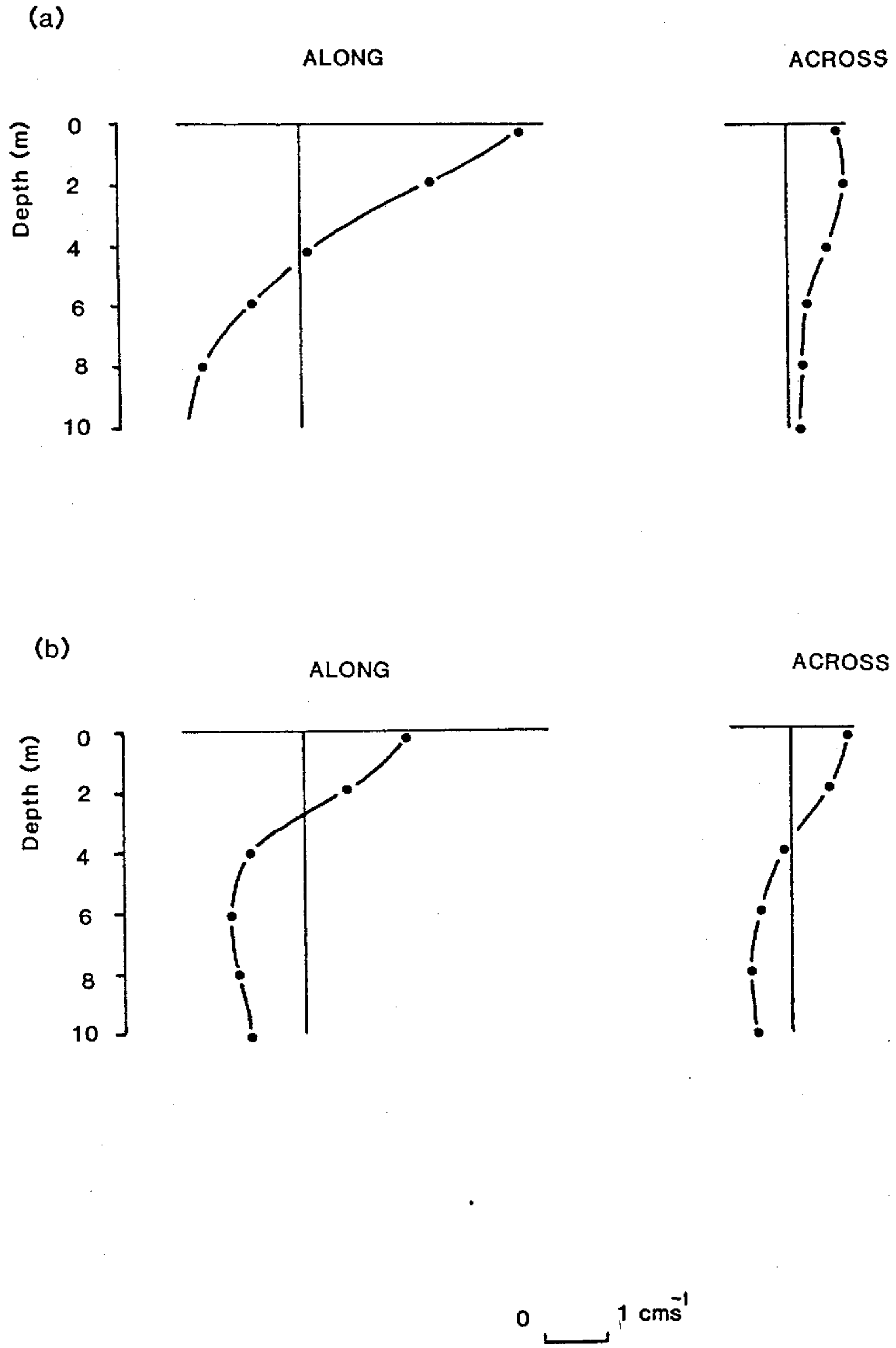
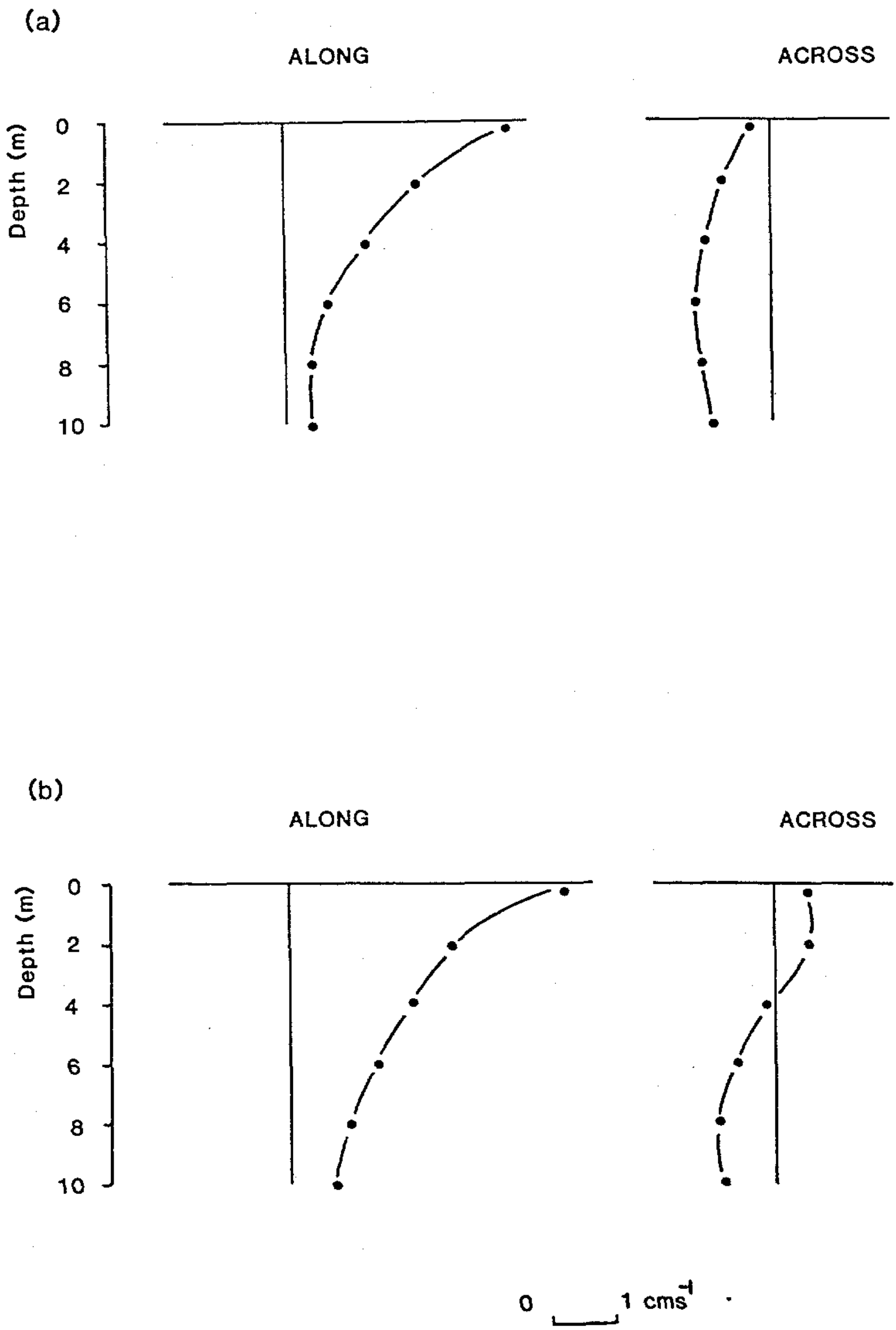

(a)
ALONG
ACROSS
Depth (m)
0
2
4
6
8
10
(b)
ALONG
ACROSS
Depth (m)
0
2
4
6
8
10
0
1 cms⁻¹

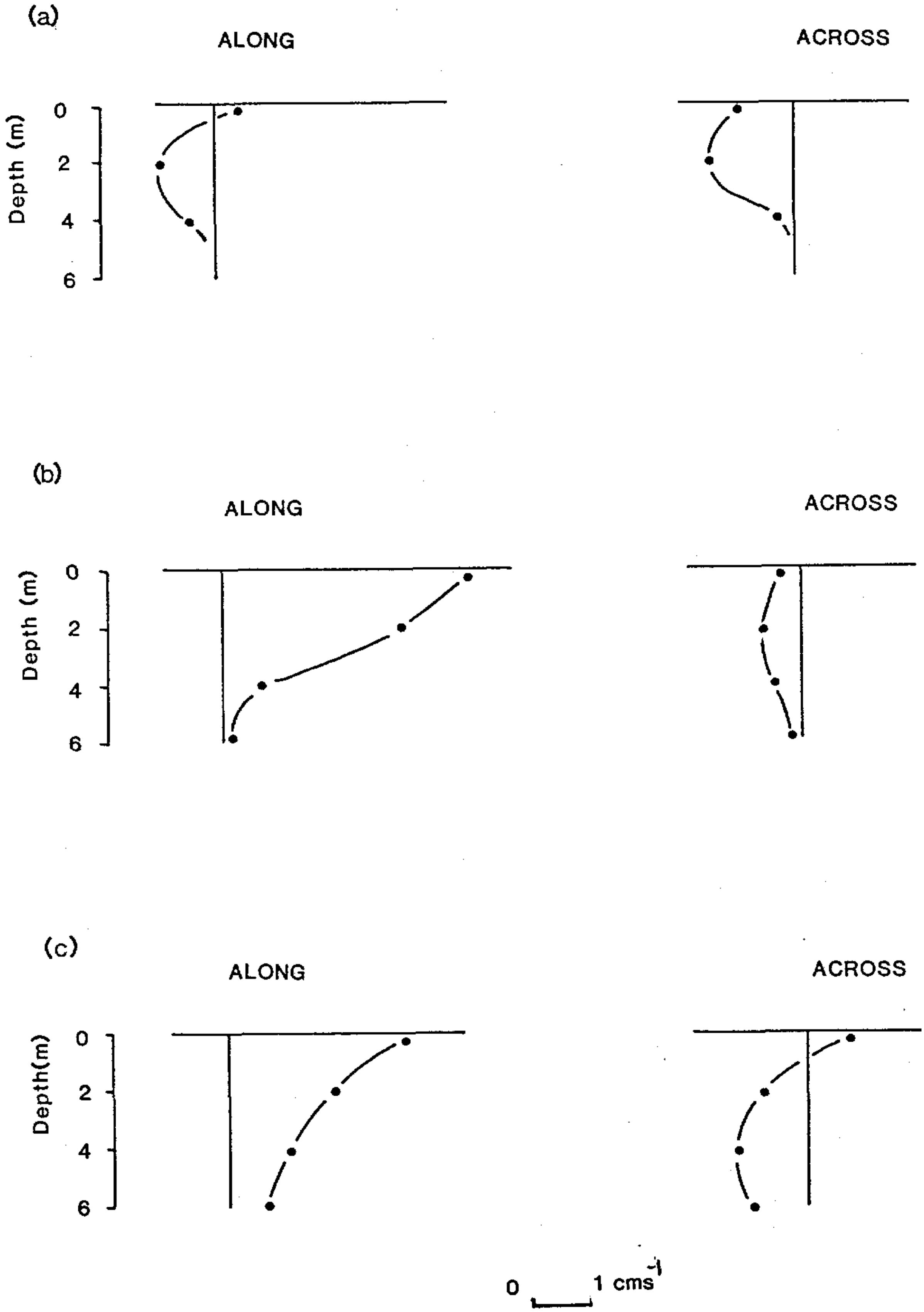
Fig. 11. Representative velocity profiles at site B. (a) 20 December 1985 (b) 20 January 1986.

Fig.11



(a)
ALONG
ACROSS
Depth (m)
0
2
4
6
8
10
(b)
ALONG
ACROSS
Depth (m)
0
2
4
6
8
10
0
1 cms-1

Fig. 12. Representative velocity profiles at site C. (a) 12 December 1985 (b) 20 December 1985 (c) 20 January 1986.


(a)
ALONG
ACROSS
Depth (m)
0
2
4
6
(b)
ALONG
ACROSS
Depth (m)
0
2
4
6
(c)
ALONG
ACROSS
Depth(m)
0
2
4
6
0
1 cms⁻¹

depth in this region will be transported away from the shore. At site C (Fig. 12) the downwind component is usually dominant but there is also a strong flow running from east to west across the lake.

Recommendations

Choosing the most appropriate depth for the outfall

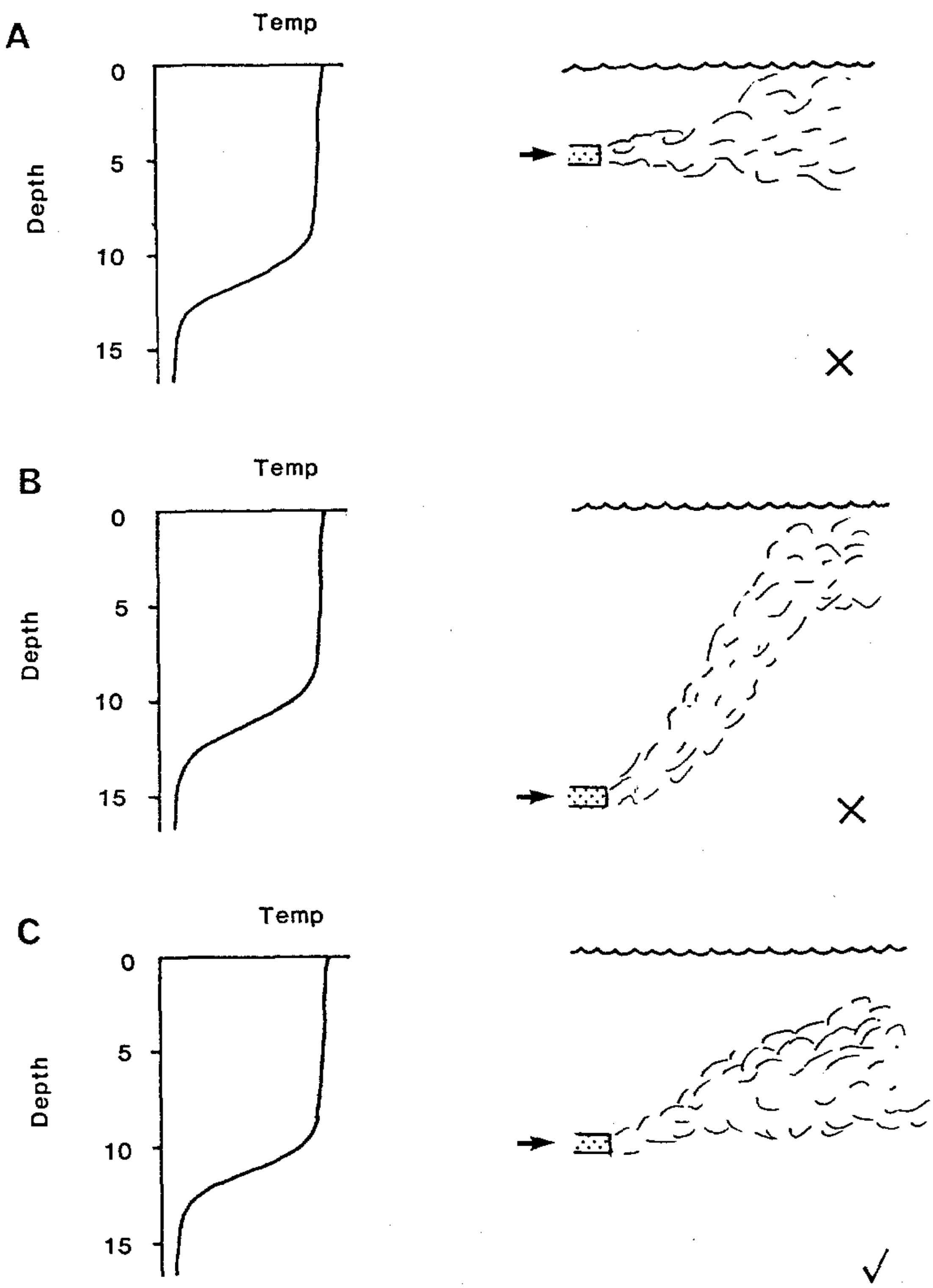
Fig. 13 shows the likely effect of discharging the effluent at three different depths in the water column. For illustrative purposes the outfall is shown as a simple open ended pipe, but more complicated arrangements would behave in much the same way. We assume that the lake is thermally stratified at the time of discharge, and the effluent is 2°C cooler than the surface water.

In Fig. 13a the effluent has been discharged at a depth of 5 m, the plume is almost neutrally buoyant and there is, initially, relatively little vertical dispersion. As the plume grows, however, some effluent is entrained in the wave-mixed layer. This could produce some surface contamination near the point of discharge so this option is not very satisfactory.

In Fig. 13b the effluent has been released at a depth of 15 m. At this depth the density difference between the discharge and the surrounding water is very great so the plume rises rapidly. The rising plume provides a very efficient means of vertical dispersion, but its upward momentum may cause it to overshoot and contaminate surface waters.

Fig. 13c shows the preferred arrangement for discharge. The storm water is released into the water column at a depth of around 10 m. The plume is still buoyant but generates less

Fig. 13. Choosing the most appropriate depth for the outfall.


A
Temp
Depth
0
5
10
15
B
Temp
Depth
0
5
10
15
C
Temp
Depth
0
5
10
15

momentum and carries the effluent to a depth where it is more or less neutrally buoyant. As the plume grows there will, of course, be some surface entrainment but by then the dilution factor will be considerable.

A number of numerical models have been developed to predict the dilution of a rising plume in weak cross-flows. (see Fischer et al 1979). These formulations can, however, only be applied when the precise configuration of the outflow port is known. In Appendix 1 we present some simple 'still-water' calculations for the dilution of a rising plume. The density parameters are taken from our measurements in Windermere but the discharge rate and the effluent concentration is hypothetical.

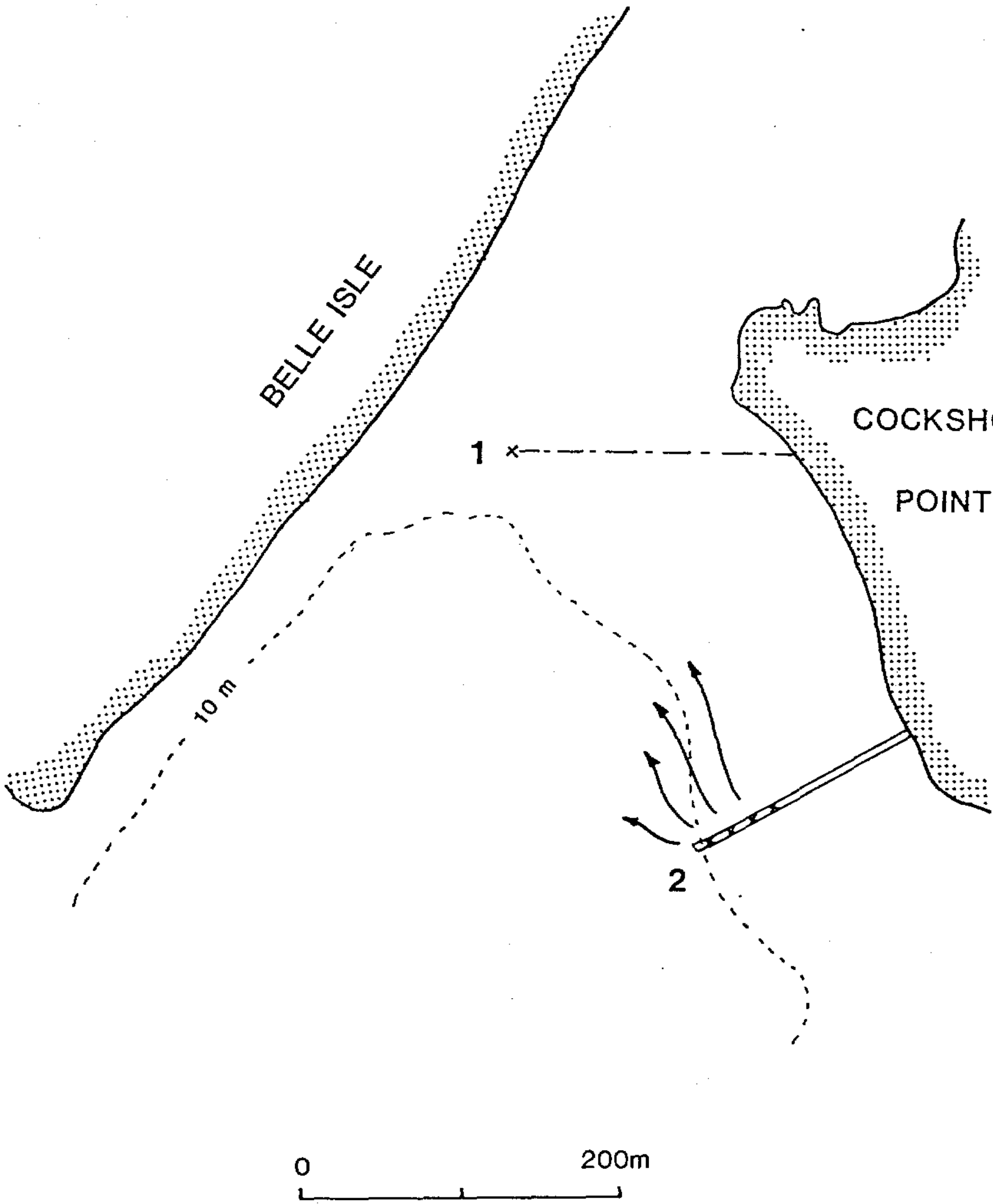
Choosing the most appropriate site for the outfall

There is no advantage in siting the outfall near the deepest part of the basin. This would require a very long pipe run and the effluent would still rise towards the surface. Fig. 14 shows two possible inshore sites for the outfall. Site 1 is the site provisionally chosen by the Authority and Site 2 is the location that we now recommend.

Site 1 is perilously close to the channel linking the Cockshot Point Basin to Bowness Bay. A discharge positioned at this site is likely to produce some shoreline contamination on Cockshot Point and could even lead to some undesirable accumulations in the boatyard area. Our velocity profiles just north of this site also suggest that this is an area of downwelling water when the wind is blowing from the south. This presents no problems, but if the wind changes to the north the same area may become a zone of upwelling water!

Site 2 may appear to be rather close to the shore, but our observations during southerly winds show that the deep currents

Fig. 14. Choosing the most appropriate site for the outfall.


BELLE ISLE
COCKSHOT
POINT
1
2
10 m
0
200m

here move away from the shore. We were unable to check the pattern of movement during northerly winds, but it is reasonable to suppose that the deeper currents would again be deflected into open water. There is an obvious risk of shoreline contamination during westerly winds. Westerlies are, however, very infrequent and the same problems would arise at the first site considered. It is important to position the outfall at site 2 as far out into the lake as possible. This lengthens the path of the surface currents to the shore, and aligns the outfall at right angles to the prevailing flow.

The design of the outfall

The simplest procedure is to release the effluent directly into the lake at a depth of 9-10 m through the open end of a pipe. This may be quite satisfactory in the short term, but could prove embarrassing if there were 'loading' problems in future. A better solution would be to discharge the effluent through a multi-port diffuser of the type frequently used in marine installations (Koh et al 1974).

A large ocean outfall diffuser is usually many times longer than the discharge depth. In Windermere it may be sufficient to space the discharge ports every few meters in the final section of pipe lying between 8 and 10 m. A comprehensive review of outfall design and diffuser hydraulics is given in Fischer et al (1979). In some installations the diffuser pipe diameter is reduced towards the end, and the discharge ports arranged horizontally to achieve better mixing. The discharge from each port in a multi-port diffuser forms a buoyant plume that can be analysed by the methods outlined in Appendix 1. Note that by reducing the volume discharged at any one point, such diffusers check the plume rise and substantially reduce the risk of surface contamination.

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Appendix 1

Some simple models of dilution in a buoyant plume.

There are a number of mathematically complex methods for predicting the trajectory and dilution of plumes discharged into moving water. Here we present some simple 'still water' solutions to highlight the key variables involved.

We assume that storm water is being discharged from an open pipe at a depth of 10 m at a rate of 10 m^3 min^{-1}. The discharge has a temperature of 16°C, the surface temperature is 18°C and the temperature at 10 m is 14°C. For illustrative purposes we will assume that the concentration of soluble reactive phosphorus in the effluent is 5000 mg m^3.

The density of water at 14°C is 999.27

The density of water at 16°C is 998.97

The density of water at 18°C is 998.62

The density gradient in the water column is therefore:

$$\varepsilon' = \frac{999.27 - 998.62}{999.27 \times 10}$$

$$= 6.5 \times 10^{-5} \ m^{-1}$$

For a round buoyant plume the buoyancy flux is:

$$B = g \ (\Delta\rho_o/\rho)Q$$

where $\Delta\rho_o$ is the difference in density between the water at 10 m and the effluent being discharged, ρ is the density of the effluent, g the acceleration due to gravity, and Q the initial volume flux i.e. the rate of discharge. In our example:

$$B = 9.8 \times \frac{999.27 - 998.97}{998.97} \times 0.166$$

$$= 4.8 \times 10^{-4} \ m^4/sec^3$$

The mass flux of soluble reactive phosphorus in the discharge is given by

$$Y = Q\,C_o = 830 \text{ mg sec}^{-1}$$

where Q is the volume flux and C_o the concentration.

In experimental studies it is possible to measure the distribution of the time-averaged concentration of a tracer in a plume. The maximum time-averaged concentration of tracer has been deduced empirically as:

$$C_m = 9.1\,YB^{-1/3}\ z^{-5/3}\ \text{mg/m}^3$$

$$= 9.1 \times 830 \times 4.8 \times 10^{-4} \times 10^{-1.66}$$

$$= 1974 \text{ mg/m}^3$$

This can notionally be regarded as the maximum concentration at the centre of the plume, but should not be regarded as a very reliable statistic.

The volume flux in the plume is given by:

$$\mu = b_3\ B^{1/3}\ z^{5/3}$$

where b_3 has an experimentally determined value of 0.15, and z is the depth of discharge.

Here: $\mu = 0.15 \times 0.081 \times 45.7$

$$= 0.55 \text{ m}^3\text{/sec}$$

The mean dilution in the plume is then:

$$\mu/Q = 3.3$$

Of greater interest in the present situation is the terminal height rise of the buoyant plume. The terminal height rise of a plume with specific buoyancy flux B can be estimated by:

$$h_B \approx 3.8\ \frac{B^{1/4}}{(g\varepsilon')^{3/8}}\ \text{m}$$

where 3.8 is a coefficient of proportionality as determined by Crawford and Leonard (1962).

In the present example

$$h_B \approx 0.148\ /\ (9.8 \times 6.5 \times 10^{-5})$$

$$= 8.9 \text{ m}$$