Water circulation and flushing characteristics of Princess Royal Harbour

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Water circulation and flushing characteristics of Princess Royal Harbour, Albany

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Summary

The safe anchorage offered by Princess Royal Harbour on the south coast of Western Australia has led to the development of the town of Albany and of associated port facilities. Pollutant wastes entering Princess Royal Harbour from industrial, municipal and rural sources resulted in widespread loss of seagrass meadows, toxic metal contamination of the harbour's food chain, and objectionable visual and bacterial pollution about some effluent outfalls.

The Environmental Protection Authority conducted a study of the pollution and ecological problems of Princess Royal Harbour and on this basis made environmental management and pollution control recommendations to the state government of Western Australia. The water circulation, mixing and exchange characteristics of Princess Royal Harbour were investigated as one component of this study in order to understand the fate and residence times of pollutants released to Princess Royal Harbour, and to assess the effectiveness of several management options. These investigations are reported here.

Measured vertical profiles of salinity and temperature indicate that the waters of Princess Royal Harbour are generally weakly stratified (in density) at sub-basin scale and are readily susceptible to vertical mixing by wind stress. The water circulation within Princess Royal Harbour (and in King George Sound, adjacent to the Princess Royal Harbour entrance channel) was measured directly by a series of drogue tracking experiments conducted under different conditions of wind and tide. These measurements revealed that the harbour has a significant barotropic response to the important forcings of wind and tide. Hence, a two-dimensional, depth-averaged, numerical hydrodynamic model of circulation in the harbour was implemented and the computer simulations compared with field measurements. General agreement between the field measurements and the hydrodynamic model simulations was found. The results of this model were then used as input to a pollutant transport model to simulate the movement, spread and loss from the harbour of dissolved pollutants.

Water volumes of up to 30 million m^3 may enter or leave Princess Royal Harbour within 8 to 16 hours on rising or falling tides, respectively. Water is accelerated as it passes through the narrow Princess Royal Harbour entrance channel with current speeds up to $0.5ms^{-1}$, which is much greater than the average tidal current speeds across Princess Royal Harbour and King George Sound. The momentum imparted to the water as it flows through this channel is an important factor in determining water exchange between Princess Royal Harbour and King George Sound.

In the absence of winds and during mean to spring flood tides, water from King George Sound is drawn in from a distance of up to 1.5km outside the entrance channel. It then passes rapidly through the channel, initially shedding vortices into the harbour, and then jets narrowly (under its own momentum) a distance of up to 2.5km directly across Princess Royal Harbour, prior to undergoing clockwise circulation during the ebb tide. Likewise, on the ebb tide, water in Princess Royal Harbour converges toward the entrance channel from a distance of up to 1.8km, accelerates through the channel and then passes into King George Sound. Early in the ebb tide the flow fans out broadly into King George Sound. As the water level falls more rapidly, outward-directed momentum flux increases and vortices are shed into King George Sound on both sides of the channel axis. Subsequently, a narrow tidal jet streams out across King George Sound and the inertia of it persists for several hours after low water, transporting water further away from the entrance channel while water close to the entrance again starts to converge on the harbour. Some of the water which formed side vortices in King George Sound on the ebb tide remains sufficiently close the harbour channel to re-enter Princess Royal Harbour on the subsequent flood tide. These vortices have been observed to form in the vicinity of the King Point wastewater outfall.

The action of wind on the harbour is an important agent of horizontal water movement. Surface water and surface-residing materials (e.g. slicks) generally move downwind. Below the surface, water circulates about Princess Royal Harbour as horizontal gyres which have a down-wind component in shallow water and an up-wind component in deeper water. Steady west to north winds generate one major anti-clockwise circulation gyre which occupies much of the harbour and east to south winds generate a major clockwise circulation. Under south-west

winds, two main gyres are established (a clockwise gyre in the north-west half of Princess Royal Harbour and an anticlockwise gyre in the south-east half). For winds which vary between these direction ranges, current directions may be decelerated or reversed and net circulation limited.

It takes only very moderate winds to modify the purely tidal circulation pattern within Princess Royal Harbour by the establishment of wind-driven topographic gyres. For example, under north to west winds, the tidal jet streaming into the harbour on the flood tide is deflected to the right (along the length of the wharf area) as it becomes entrained into the anticlockwise wind-driven circulation. A portion of this newly introduced water is retained during the subsequent ebb tide and water leaving the harbour is derived predominantly from the southern side of the entrance. For east to south winds, the flooding tidal jet is diverted southward and much of the ebbing water is derived from in front of the wharf. The combined influence of wind and tide on the water movements is of great importance to the flushing of the harbour.

Likewise, wind-driven circulation in King George Sound can modify the tidal jet flows emanating into the Sound. From field measurements it appears that south-west to south-south-east, or north-north-west to north-east winds are efficient in driving water circulation in the western portion of King George Sound. These directions are approximately parallel to the general coastal alignment of this part of the Sound. South-west to south south-east winds induce marked water flow to the north (3-4 km excursions observed) through Middleton Bay. To a lesser extent, north north-west to north-east winds induce a southward flow of water.

The movement of effluent discharged to Princess Royal Harbour is determined by the effluent characteristics (e.g. buoyant, dissolved, settling), its rate of dilution and its transport by the water movements. Buoyant pollutant materials (e.g. fat, oil, grease) remain at or near the water surface and move down-wind except when caught in strong tidal currents, e.g. in the entrance channel. Dissolved or fine, suspended pollutants are more uniformly distributed throughout the water depth, reflecting the ability of the wind to mix the water vertically. The movement of these dissolved and suspended materials is predominantly influenced by wind-driven horizontal gyres and tidal currents.

The dissolved/suspended effluent discharged to Princess Royal Harbour emanates mainly from industrial outfalls on the north shore or an agricultural drain to the north-west of the harbour. In winter under north-west to west winds, these materials tend to be transported about the harbour in an anti-clockwise direction moving about the south-west side of the harbour, before circulating back toward the harbour entrance. In summer under east to south-east winds, these materials initially move clockwise along the northern shore and once near the entrance, may be either transported back into the harbour during a flood tide or flushed from the harbour during an ebb tide.

Computer simulations of the transport and dispersion of dissolved materials were run for simplified conditions of steady wind and tide yielding 90% flushing times of about 10 days. In reality (a) winds are variable and the resultant water circulation in Princess Royal Harbour less coherent than for steady wind, (b) tidal range varies, and (c) on each flood tide there is some re-entry of water which left the harbour on the previous ebb tide. Because of these factors a 90% flushing time in the range 10-20 days is estimated. Flushing times are typically much greater than the time scales of nutrient uptake by benthic algae. In winter, flushing times do not depend much on the current locations of effluent discharge because wind-driven effluent mixing about the harbour dominates immediate tidal flushing. A different relationship is likely to apply under summer wind conditions.

Under south-west to south-east winds the diluted wastewater from King Point may be advected away from the Princess Royal Harbour entrance, but into Middleton Bay, a favoured recreational area.

The ability of the wind to vertically mix the waters of Princess Royal Harbour implies that dissolved and suspended nutrients discharged to the harbour are also well mixed and that these nutrients are in frequent contact with and are available to the bottom-dwelling plant communities.

Under moderate wind conditions the wave induced bottom currents and the largescale circulation currents are weak and are unlikely to mobilise the benthic algae located at or below the mean depth of the harbour. Mobilisation of these algae presumably occurs episodically under gale force winds.

Seagrass meadows retard water movement and provide a depositional environment for fine organic particulates. Nevertheless, even in very shallow water appreciable currents can still be generated at the level of the seagrass canopy and above fully submerged meadows.

The tidal rise and fall of water levels within and outside Princess Royal Harbour are very similar. Hence, a widening or deepening of the existing entrance channel would not result in an increase of flow through the channel (because the tidal capacity of the harbour would remain unchanged) and the speed of water flowing through the channel would decrease. This may adversely affect the penetration of the jet flow and the net amount of exchange between these two bodies of water.

Deepening (dredging) the harbour in areas of heaviest benthic algae accumulation (presently 2-5m depth) may also result in reduce flushing. A harbour with more uniform bathymetry would lead to a reduction in the strength of the horizontal wind driven circulation, a weakening of mixing in the harbour and hence a reduction in the flushing capacity of the harbour.

Effluent from the municipal wastewater outfall at King Point (located in King George Sound in the vicinity of the Princess Royal Harbour entrance passage) may be partially entrained in tightly circulating vortex-type flows formed near the harbour entrance during ebb tide and this effluent may enter Princess Royal Harbour on the subsequent flood tide. King Point is just within an estimated outer radius of water abstraction (into Princess Royal Harbour) for the flood tide; therefore, some wastewater discharged on the flood tide may also enter Princess Royal Harbour. Likewise, effluent initially discharged from within the harbour may leave and then a proportion be drawn back into Princess Royal Harbour on the subsequent flood tide. However, the existence of a narrow harbour entrance channel and of an ebb tidal jet reduces the amount of re-entry.

1. Introduction

1.1 General

As shown in Figure 1 the town of Albany on the south coast of Western Australia overlooks the protected waters of Princess Royal Harbour and King George Sound. The townsite was originally chosen because of the safe anchorage afforded by the harbour on an otherwise rugged and inhospitable coast. Nowadays, the developed Port of Albany is a major outlet for grain and superphosphate. The harbour is used for commercial and amateur fishing and provides opportunities for a wide range of waterbased recreational activities. These opportunities and the scenic qualities of the harbour contribute to the tourist potential of the town and the region thus enhancing the local economy. Industries including a superphosphate plant, woollen mills, abattoirs and food processing works have been sited near the foreshore of Princess Royal Harbour. Some of these industries discharge effluents directly into the harbour waters.

There has been concern for some years over the effects of effluent discharges on the quality of the biota, sediments and waters, and on the ecology of Princess Royal Harbour. Investigations have been conducted on the nutrient and bacterial status of the waters (Atkins *et al*, 1980), heavy metal contamination of molluscs, fish, seagrasses and sediments (Talbot, 1983; Jackson *et al*, 1984; Talbot *et al*, 1987) and the loss of seagrasses in Princess Royal Harbour (Bastyan, 1986, Kirkman, 1987).

In response to these findings the Environmental Protection Authority (EPA) prepared an overview report on the state of environmental problems in the Albany harbours (Mills, 1987). In 1988 the Western Australian Government approved funding for an intensive two-year study into the pollution and ecological problems of the Albany harbours. The findings of this study are contained in a report from its Technical Advisory Group (1990). The Environmental Protection Authority (1990) then submitted to Government its management recommendations in relation to these problems.

Mills and Brady (1985) carried out a study on the wind-induced movement and circulation of Princess Royal Harbour waters. The present report documents a more detailed investigation of the circulation patterns, water exchange characteristics and flushing times of the harbour. Such work was required to increase understanding of the dispersion and flushing of materials released to these waters and to provide a firmer basis on which to develop environmental management and pollution control strategies for the harbour. This hydrodynamic investigation of Princess Royal Harbour formed a component of the Albany Harbours Environmental Study 1988-1989 (Technical Advisory Group, 1990) co-ordinated by the Environmental Protection Authority.

1.2 Objectives and scope

The objectives of this study were to:

- characterise water circulation and mixing within and immediately outside Princess Royal Harbour;
- estimate water exchange between Princess Royal Harbour and King George Sound; and
- use this knowledge to understand the dispersion and flushing of pollutant materials released to these waters.

The hydrodynamic investigation included the following tasks:

- field measurement of water movements within and outside Princess Royal Harbour under a range of tidal and wind conditions. Free-moving drogues were tracked for periods of six to 36 hours to gauge the speed and patterns of water movement. Analysis of vertical profile data for salinity and temperature to determine the density layering of the water and the efficiency of wind-driven vertical mixing of the water column;

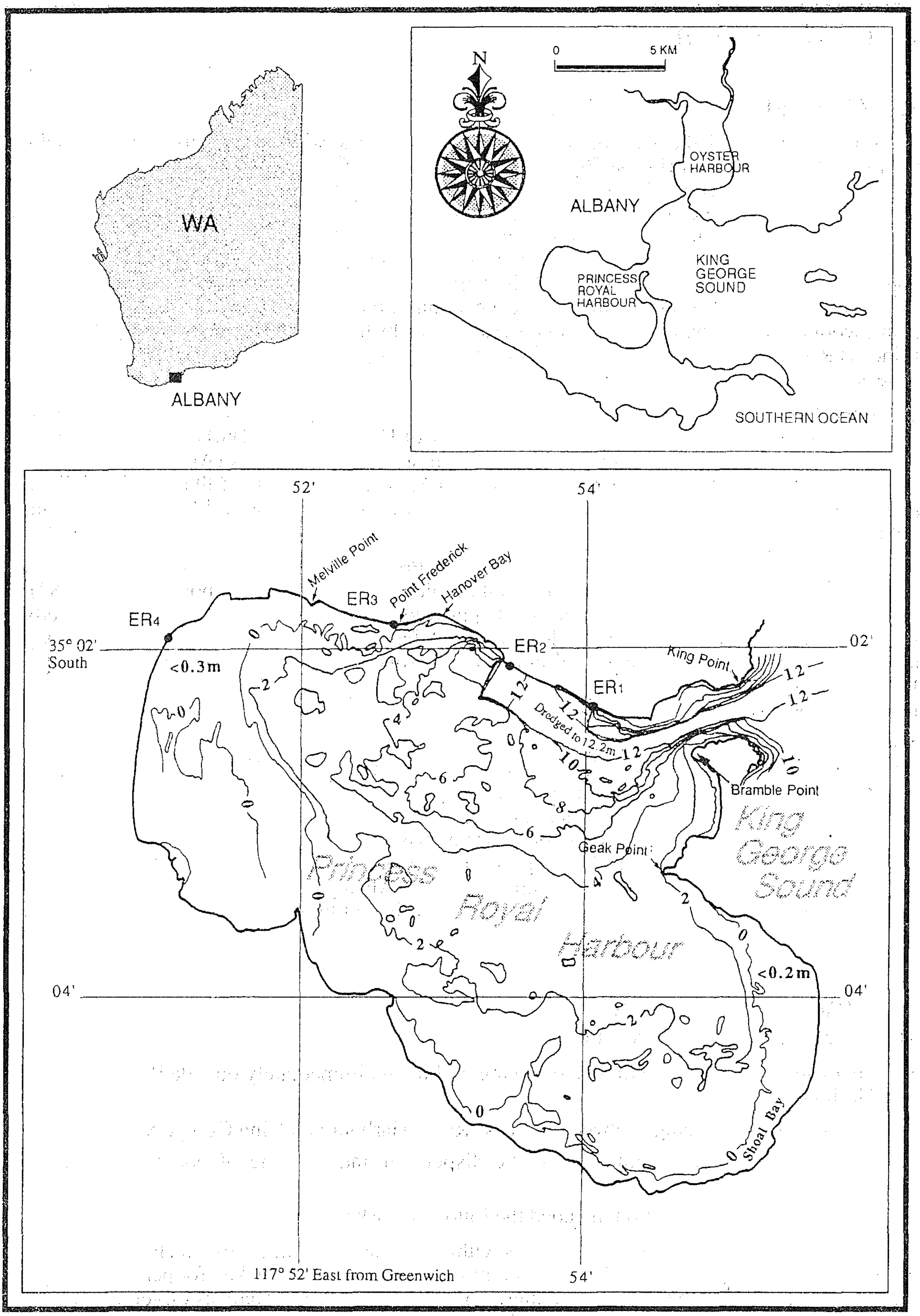

Figure 1: Map of Princess Royal Harbour with bathymetry and effluent release (ER) points modelled

- computer simulation of water circulation patterns in Princess Royal Harbour induced by wind and tidal forcing; and
- computer simulation of pollutant transport within Princess Royal Harbour and flushing from Princess Royal Harbour into King George Sound.

1.3 Study area

Princess Royal Harbour is a large (28.8 km^2) almost land-locked bay situated on the south coast of Western Australia (Figure 1). It is approximately elliptical in shape, being eight kilometres long in a north-west to south-east direction, and four kilometres wide. Princess Royal Harbour has an average water depth of 3.1m at mean sea level, and comprises a deep basin, bordered by a shallow, intertidal to subtidal margin which is most extensive off the western and southern shores. The harbour has a short, narrow entrance passage (minimum sectional area 3.47×10^3 m^2) into King George Sound (KGS). Through this entrance, a shipping channel is maintained to 12.5m depth, and within the harbour a turning basin has been dredged to 12m, adjacent to the port wharfs on the north-east shore.

No major rivers discharge into Princess Royal Harbour; the sources of fresh water are from direct precipitation, seepage, and local surface runoff, especially via the Elleker Road drain.

1.4 Climate

The average annual rainfall for Albany is 936mm and most rain falls during the period of May to October. Evaporation is strongly seasonal peaking in the summer months with a mean annual value of approximately 1200mm (Bureau of Meteorology, 1984).

Albany has mild summers and mild winters with mean daily maximum air temperatures of 25.8°C for January and 15.5°C for August.

The Bureau of Meteorology has prepared per cent occurrence matrices of surface wind speed and direction observations taken twice daily (0900 and 1500) at the Albany airport for a period of 19 years. At the time of field measurements this was the only available set of analysed, long-term wind data for the Albany area. It should be noted however, that the airport is located some 13km away from the coast. Prevailing wind directions at Albany airport vary throughout the year. From December through to the end of March winds are generally easterly in the morning, swinging to south-easterly in the afternoon. During the period April to August the winds typically move from north-westerly to westerly and from September to November morning westerlies give way to afternoon south-westerlies. Moderate wind speeds are experienced throughout the year typically about 3-5ms^{-1} in the morning and increasing to 5-7ms^{-1} in the afternoon. Autumn is the season of weakest winds and most frequent calms. High wind speeds (greater than 12.5ms^{-1}) may occur at several times of the year but only for a small proportion of the total time.

More recently, Pattiaratchi (1991) has performed statistical analyses on hourly wind velocity data from the Sand Patch Peak wind station for the period 23 March 1990 to 22 January 1991. That wind station was operated by the State Energy Commission of Western Australia. Pattiaratchi's (1991) analysis shows that for the 300 day sample period winds were less than or equal to 5ms^{-1} for about 32 % of the records and less than or equal to 8ms^{-1} for about 54 % of the records.

1.5 Hydrology of Princess Royal Harbour

Waters occupying the main Princess Royal Harbour basin are essentially marine with salinities differing only slightly from those measured in King George Sound (Atkins *et al*, 1980, Hillman *et al*, 1991a). This reflects the absence of major riverine inputs to the harbour.

Water temperature reported by Atkins *et al* (1980) for the Princess Royal Harbour basin range from 12.5°C (July) to 20.4°C (January). The Princess Royal Harbour water temperature cycle appears to be strongly influenced by that of the local air temperature whereas the data reported by Pearce (1986) for water temperatures on the inner continental shelf (55m depth) off Albany indicate that a warmer temperature trough occurs about September.

Salinity and temperature depth profile measurements were collected at five stations in Princess Royal Harbour at monthly intervals from December 1987 to February 1989 by the Centre for Water Research of the University of Western Australia, as part of the EPA's environmental investigations of the Albany harbours. These data are presented in Hillman *et al,* (1991a). Although temperature and salinity gradients were present on each occasion, the vertical density stratification was generally weak and did not occur on a basin-wide scale. On most occasions vertical stratification was confined to sub-regions of the harbour. Vertical (top to bottom) density differences in stratified areas of Princess Royal Harbour generally ranged from 0.1 to 0.5 kg m^{-3}. Only on two sampling occasions was the vertical stratification basin-wide. One of these followed a flood event in June 1988 where the density differential in the harbour reached 2 kg m^{-3}.

1.5.1 Wind mixing

The response of stratified water bodies to wind stress can be predicted according to a Wedderburn number, W, classification scheme (Imberger and Hamblin, 1982). W is given by

$$W = (g'h/u^{*2}).(h/L);$$

where g' ($= g\ \Delta\rho/\rho$) is the reduced acceleration due to gravity of the density jump ($\Delta\rho$) at the base of the surface layer which has a depth h, and L is the fetch length of the wind. The parameter u^* is the water shear velocity induced by the wind at the surface (e.g. Fischer *et al*, 1979).

Based on laboratory and field experimental verification in lakes as reviewed by Imberger and Patterson (1990), a W greater than order 1 implies that the stratification will be only slightly perturbed by gentle wind forces. As W approaches and becomes less than order 1, the surface stratification will become progressively more severely perturbed by downwind surface advection with upwelling of bottom waters at the upwind end and strong vertical mixing. Spigel and Imberger (1980) pointed out that for values of W less than one interfacial (shear) mixing dominates.

Parameter value combinations were selected from the range of values generally observed in Princess Royal Harbour to obtain maximum values for W. Under most conditions monitored by Hillman *et al* (1991a) (not including an intense flood event in June 1988) $\Delta\rho < 0.5$ kg m^{-3}. To calculate an upper value for W an initial upper mixed layer depth of 3m was used. A minimum Princess Royal Harbour fetch length is 4000m. A light to moderate wind speed of 5ms^{-1} was considered to be common. These parameter values showed that the Wedderburn number in Princess Royal Harbour is generally less than 0.6 indicating that interfacial shear dominates the wind-induced vertical mixing process.

For surface layer deepening dominated by shear ($W < 1$), the deepening law as originally introduced by Pollard *et al* (1973) for a two-layer fluid with a homogeneous upper layer and a linearly stratified lower layer is:

$$h(t) = (2C_s / N_o{}^2)^{1/4}\ u^*\ t^{1/2};$$

where $C_s = 0.24$ is a constant that determines the efficiency of energy conversion (Imberger and Patterson, 1990) and $N_o{}^2$ is the buoyancy frequency squared.

Using this formula, calculations were performed to determine the deepening of the upper mixed layer under a range of wind speeds and durations. The results are shown in Table 1.

Table 1: Wind mixing of the upper mixed layer in Princess Royal Harbour, for typical density stratification, under a range of wind speeds and durations.

Duration of wind (hours)	Increase in upper mixed layer depth (m) Wind speed = 5 ms^{-1}	Increase in upper mixed layer depth (m) Wind speed = 10 ms^{-1}
1	1.7	3.4
4	3.4	6.8
9	5.1	10.2

The average depth of Princess Royal Harbour is 3.1m. Hence, the calculations presented in Table 1 suggest that even light to moderate winds acting for as little as 4 hours can vertically mix the entire water column over substantial areas of the harbour. These calculations are consistent with the observations that the density structure is not generally of basin-scale. Based on this analysis, it is expected that the barotropic response of the harbour to wind and tide is generally active and of significance although some baroclinic transport is also likely to be present.

1.6 Water level variations

The astronomical tide at Albany (Princess Royal Harbour) is 'mixed', being neither consistently diurnal nor semi-diurnal and the tidal range rarely exceeds 1.1m.

Easton (1970) conducted an harmonic constituent analysis of tidal data from Albany. The constant values for the five constituents of greatest amplitude are shown in Table 2. It can be seen that the diurnal constituents 01 and K1 are somewhat larger in amplitude than the semi-diurnal constituents M2 and S2 but of the same order.

Table 2: Tidal constants for the five largest harmonic constituents of the Albany tide (after Easton [1970])

Constituent	Amplitude (m)	Phase (°)
01	0.143	307.0
P1	0.057	325.5
K1	0.191	328.8
M2	0.075	329.4
S2	0.108	330.0

Based on the results of tidal analyses of data from many ports, Easton (1970) divided the Australian coastline into zones of similar tidal characteristics. One of these zones, the south Western Australian zone, encompasses the ports of Albany, Bunbury and Fremantle. Hearn *et al* (1985) discussed the Bunbury tide in some detail. A similar discussion of the tidal characteristics at Albany is given here.

The frequency of the K1 tidal constituent exceeds a true diurnal frequency by one cycle per year and therefore the time of day occurrence of high water due to K1 alone varies with an annual cycle. Further, the astronomical argument of K1 at the beginning of each year remains at about 10°. Thus, at Albany, on 1 January of each year the K1 high water occurs at approximately 2115. As each year advances, the K1 high water occurs at a progressively earlier time of day, happening at about 0915 mid year and returning via the small hours of the morning to about 2115 by the end of the year.

The frequency of the 01 constituent differs from a true diurnal frequency by nearly 26 cycles per year. Therefore its time of high water occurrence undergoes a cycle of about 14 days duration.

The interaction of the 01 and K1 constituents leads to a 13.7 day neap-spring cycle, within which the range of the diurnal tide varies between 0.67m and 0.10m. The high water of the diurnal spring tide generally occurs within 20 minutes of the K1 high water, and therefore follows a similar time of day progression throughout the year. Hence, falling spring tide occurs late night/early morning in summer and during the day in winter.

Another neap-spring tidal cycle of 14.7 days duration results from the interaction of the semi-diurnal constituents M2 and S2. The tidal ranges within this cycle vary between 0.37m and 0.07m. In January and July the diurnal and semi-diurnal spring tides occur at the same time (and the respective high waters occur within 2.5 hours), whereas in April and October the diurnal spring tide coincides with the semi-diurnal neap tide.

Many of the features observed in the tidal records at Albany may be explained in terms of a combination of diurnal and semi-diurnal tides with the properties described above. In particular, it is possible to explain the alternating dominance of the diurnal and semi-diurnal tides, the variations in the spring tidal ranges throughout the year and the marked and varying asymmetry of the tidal rise and fall. These features and their relationship to the neap-spring cycles of the diurnal and semi-diurnal tides are summarised in Table 3 for the months of January, April, July and October.

Table 3: Some major features of the vertical tide at Albany

Month	Tidal Type	Spring Range	Tidal Water Level Asymmetry*	Comment
January	Mainly diurnal	1.2m	Slow rising (day/16h) Fast falling (night, early morning/9h)	Semi-diurnal & diurnal springs coincide
April	Alternating diurnal & semi-diurnal	0.9m	Fast rising (morning/10h) and slow falling (afternoon, night & early morning/15h) during predominantly diurnal tides	Semi-diurnal neaps & diurnal springs coincide
July	Mainly diurnal	1.1m	Slow rising (night, early morning/16h). Fast falling (day/9h)	Semi-diurnal & diurnal springs coincide
October	Alternating diurnal & semi-diurnal	0.8m	Fast rising (mid-afternoon to night/10h) & slow falling (morning/14h) during predominantly diurnal tides	Semi-diurnal neaps & diurnal springs coincide

*the durations of rising and falling water level are generally unequal and are indicative only

Water levels on the open coast vary under the influence of local and remote meteorological and oceanic events. Variations of periods longer than a few hours will be transmitted into Princess Royal Harbour with negligible attenuation and will contribute to the water level history as recorded at the port.

Provis and Radok (1979) reported the presence of non-tidal sea-level variations of the order of 0.5m at Albany. These variations were shown to have periods ranging from one to 365 days.

The extreme range of all water levels recorded at Albany between 1951 and 1968 was 2.0m (Easton, 1970), about twice the maximum astronomic tidal range. Over the three year period from 1966 to 1968 the extreme range was 1.7m.

Winds acting directly on Princess Royal Harbour cause a slope in the water surface with set-up against downwind shores and set-down against upwind shores. Mills and Brady (1985) have shown that wind-induced water level differences across the harbour are typically about 0.03m, but may range up to about 0.3m under storm conditions. Variations in wind strength and direction give rise to standing waves in the harbour.

1.7 Water movements - general

Until recently there was no systematic knowledge of water movements in Princess Royal Harbour. However, Mills and Brady (1985) showed that local winds can generate appreciable lateral water circulation within the harbour. The patterns of wind-induced circulation are determined by the wind direction and by the orientation and bathymetric variation of the harbour (Figure 1). In addition to these factors, the speed and persistence of the wind determines the strength of the circulation. Currents in shallower parts of the harbour tend to be driven down-wind and return (up-wind) flows occur in deeper water. Winds with directions from north to west promote a large anti-clockwise circulation about the harbour, whereas winds from the south to the east promote a dominant clockwise circulation. In each of these cases there is a significant wind forcing component along the major (longitudinal) axis of Princess Royal Harbour. South-west winds which traverse the width of Princess Royal Harbour favour the development of two main counter-rotating gyres with water flow directed up-wind in the deeper central portion of the harbour. These various wind-driven circulation patterns are important agents of broad horizontal mixing over most of the Princess Royal Harbour basin (depths exceeding 2m). They can also extend over the western shallow margin of Princess Royal Harbour while the banks and seagrass beds of this margin are submerged.

The barotropic analysis of Hunter and Hearn (1987) also suggests that the bathymetric form of Princess Royal Harbour will respond to wind forcing dominantly as a lateral circulation rather than a vertical overturning circulation.

Little is known of tidal currents in the area. Measurements and scaling analysis indicate that in unconstricted coastal waters around south-western Australia, the tidal currents are very weak and are of the order of $0.01ms^{-1}$, as well as being dominated by wind-induced and (in some circumstances) continental shelf currents (e.g. Steedman and Craig, 1983). However tidal currents (and currents induced by other components of sea level change) may be of great local importance where bays, inlets or estuaries of large plan area open to the sea through narrow entrance channels (e.g. Hearn *et al*, 1985). Since Princess Royal Harbour has such a form, its tidal currents warrant investigation to determine their ability to transport and flush materials from the harbour.

2. Methods

2.1 Field methods

2.1.1 Salinity and temperature measurements

Hillman *et al* (1991) measured vertical profiles of salinity (±0.1‰) and temperature (±0.1°C) at 1m intervals throughout the water column using a portable salinity-temperature meter (Model 602, Yeo-Kal Electronics Pty Ltd, Australia) calibrated with standard seawater.

2.1.2 Droguing

Current velocity and water circulation patterns in Princess Royal Harbour were obtained by deploying drogues and plotting their horizontal trajectories over periods of six to 36 hours. Each drogue consisted of two perpendicularly crossed sails (generally $4m^2$ in area) attached with thin wire trace to a numbered surface marker float and set at a predetermined depth below the water surface. The floats (hemispherical of a radius of 15cm) were designed to present minimal resistance to the wind. Typically 6 to 10 drogues were deployed on a given day (at two or more depths) and their positions fixed (±2m) successively using a tracker boat and a radio trisponder position fixing system. Where possible, the position of each drogue was determined at least once every 45 minutes. Only a small subset of the drogue tracking results are used in this report. However, a list of all drogue deployments internal and external to Princess Royal Harbour is given in Appendix 1.

2.1.3 Moored current meter measurements

Four Neil Brown Instrument Systems acoustic current meters (Model ACM-2) were moored in King George Sound. These instruments record five minute averages of the northerly and easterly components of the current vector ($\pm 1cm\ s^{-1}$). A thermistor senses *in situ* water temperature (±0.5°) and this is recorded every 50 minutes.

2.1.4 Current meter profile measurements

An Ogawa-Seiki profiling current speed and direction meter was used to measure water currents in the Princess Royal Harbour entrance channel. The measurements were conducted from a small boat anchored in the middle of the dredged shipping channel near the channel section of minimum area. Profiling was conducted at depth intervals of one metre over the total water depth of 12.5m. On each day of measurement repeated profiles were taken over a period of approximately nine hours spanning ebbing and flooding tide conditions.

2.2 Numerical models

2.2.1 Hydrodynamic model

A two-dimensional, depth-averaged numerical hydrodynamic model described in Mills (1985) was used with spatial resolution of 200m to simulate water movements in Princess Royal Harbour forced by sea level variations and local wind stress. The analysis of wind-induced vertical mixing in the harbour (see Section 1.5) provided a justification for the use of this barotropic model. It was assumed that the sea level variation at the harbour entrance incorporated all external barotropic forcing effects on the harbour arising from the astronomical tide or other meteorological and oceanographical effects. The model was 'forced' directly by surface wind stress and by specifying flow across the model open boundary which was chosen to represent the minimum cross-sectional area of the entrance channel. The specified flow was consistent with sea level variation at the harbour entrance and the volumetric prism characteristics of the harbour. Appendix 2 contains further details relating to the implementation of the hydrodynamic model to this study.

2.2.2 Transport model

A two-dimensional Lagrangian particle tracking technique (Hunter, 1987) was modified and used to predict the dispersion of dissolved contaminant discharged at several locations in Princess Royal Harbour and to estimate pollutant flushing times for Princess Royal Harbour. This model simulates a continuous cloud of dispersed "contaminant" by an ensemble distribution of discrete particles. The (spatially and time dependent) depth-averaged current velocity results from the hydrodynamic model are used by the transport model to calculate the advection of the particles about the harbour. Turbulent diffusion of the particles is simulated with stochastic methods. Contaminant transport simulations can be run for specific conditions of wind and sea level hydrodynamic forcing, and for specific contaminant release points within Princess Royal Harbour. Flushing times of dissolved contaminants can be defined as the time taken to "lose" a given percentage of particles by export through the harbour mouth. For further details refer to Appendix 3.

3. Tide induced flow in Princess Royal Harbour

Flows through the Princess Royal Harbour entrance channel are driven by pressure gradient forces which occur when the water levels at opposite ends of the channel differ. These level differences are initiated mainly by variations in the external (outside Princess Royal Harbour) water level. The frictional impedance of the entrance channel controls the relationship between channel flow and water level differential. Simple calculations show that the water level differential required to drive tidal flow through the Princess Royal Harbour entrance is at most a few millimetres. Therefore, the range of the tide within the harbour closely approximates that of the external tide.

Princess Royal Harbour has a surface area of $2.88 \times 10^7 m^2$ and experiences a spring tidal range in excess of 1m. Hence, the volume of water stored in Princess Royal Harbour can change by $3 \times 10^7 m^3$ in about 12 hours as a result of flow through the entrance channel. In this case, average flow rate through the channel would be about $700 m^3 s^{-1}$ and an average current speed of about $0.2 ms^{-1}$ would occur at the channel cross-section of minimum area ($3.5 \times 10^3 m^2$). This is confirmed by current meter profiling data from the harbour entrance which indicates that the flow is generally uni-directional from surface to bottom. Such speeds are an order of magnitude greater than maximum tidal speeds recorded by the Environmental Protection Authority long-term, moored current meters in the unconstrained coastal waters of King George Sound (Pattiararchi *et al*, 1991). Under a spring flooding tide, the average specific momentum influx (i.e. the average product of volume inflow rate and current speed) across the smallest channel section into Princess Royal Harbour is about $160 m^4 s^{-2}$. This momentum inflow acts like a force in that it drives net water circulation within the harbour. The strength and extent of this circulation, and its role in water mixing and exchange will now be examined with the aid of a numerical hydrodynamic model and with field measurements.

3.1 Numerical simulations of tidally-induced flow in Princess Royal Harbour

3.1.1 Diurnal tide of range 1m

The hydrodynamic model was used to calculate horizontal, depth-averaged currents in Princess Royal Harbour associated with a vertical tide of amplitude 0.5m (range 1m) and period 24 hours, oscillating sinusoidally about mean sea level. This is a simplified representation of the mainly diurnal spring tides at Albany which were described in greater detail in Section 1.6.

Figures 2-9 show the model results for the instantaneous water current distributions in Princess Royal Harbour at successive three hour intervals (one-eighth of the tidal period). Blank areas where no current vectors have been drawn represent the locations and extent of exposed intertidal flats during periods of low water level.

At the time of low water (LW) there is no volume and no momentum flow through the entrance to the harbour. Figure 2 shows that at time of low water, current speeds in Princess Royal Harbour are generally very low with the root mean square (rms) speed of currents throughout the harbour being $0.01 ms^{-1}$.

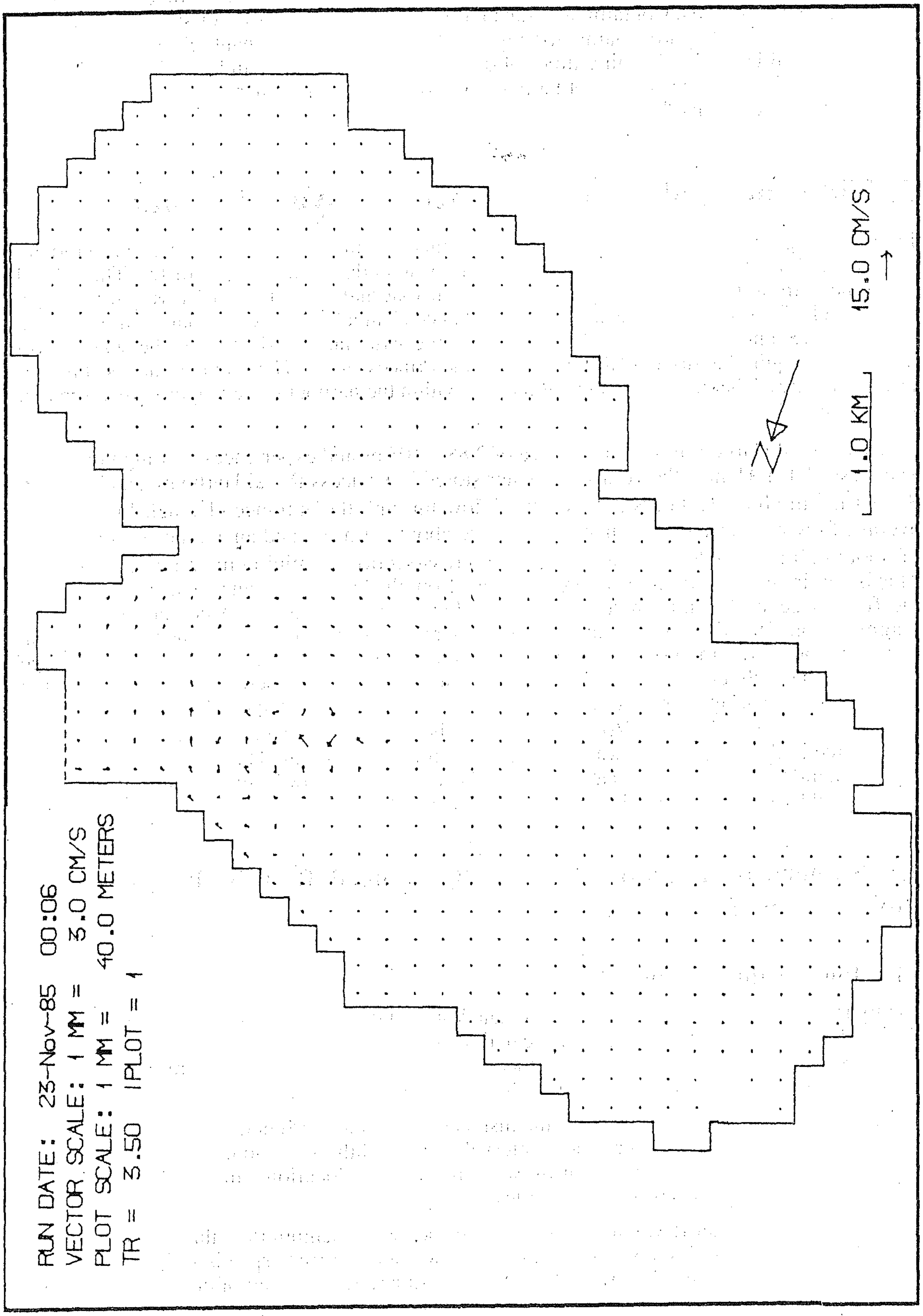

Figure 2: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water.

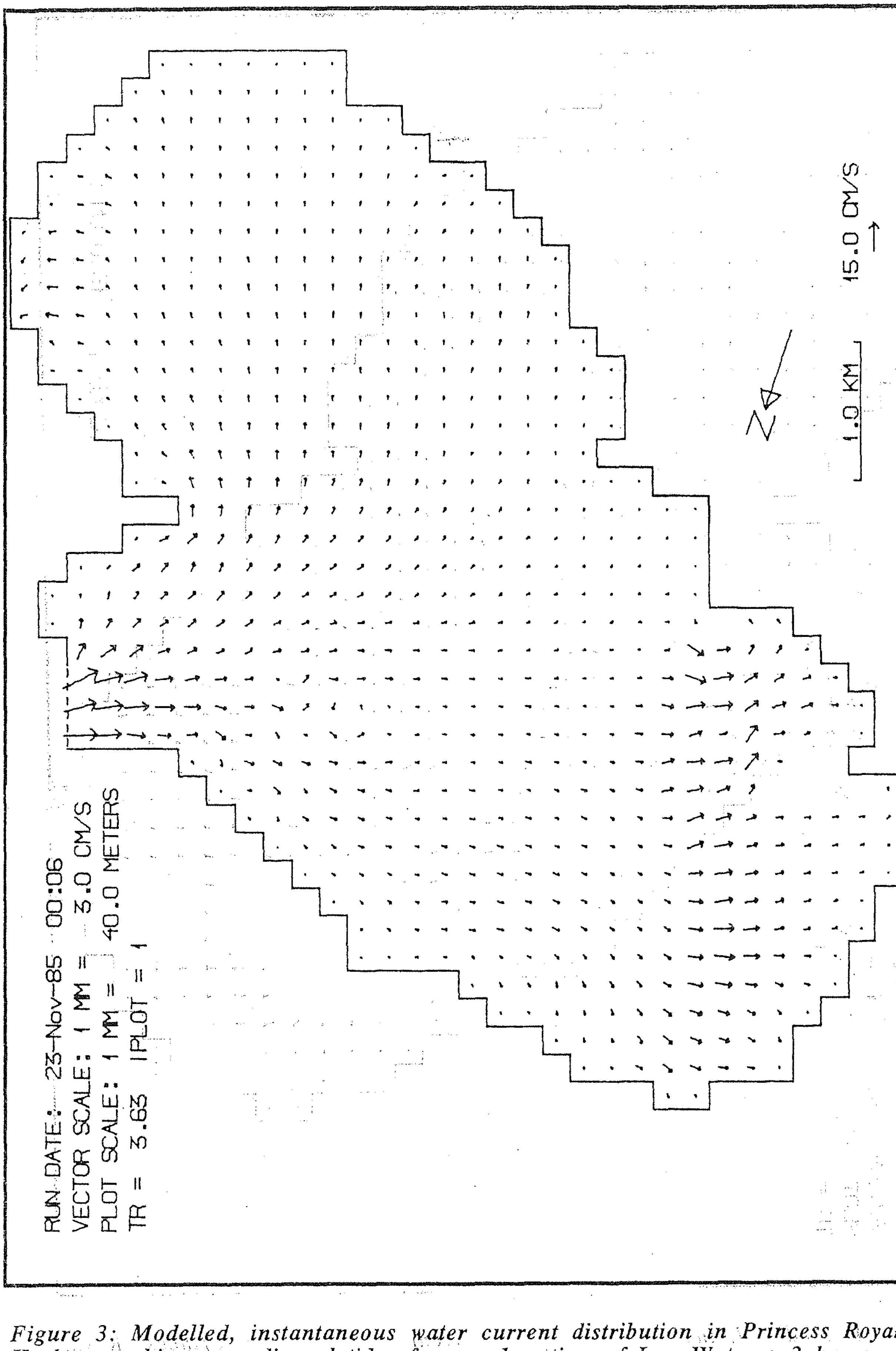

Figure 3: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water + 3 hours.

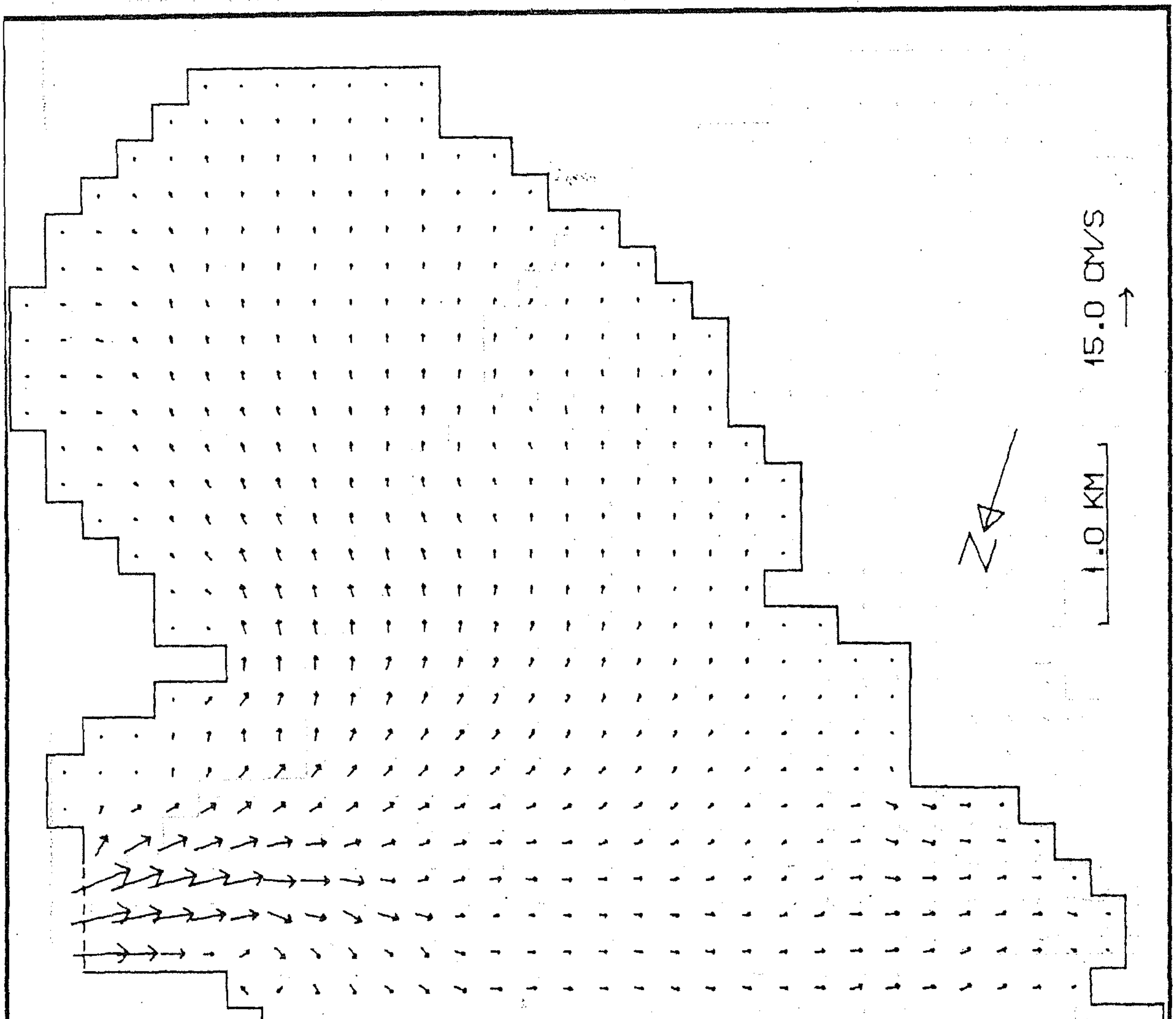

Figure 4: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water + 6 hours.

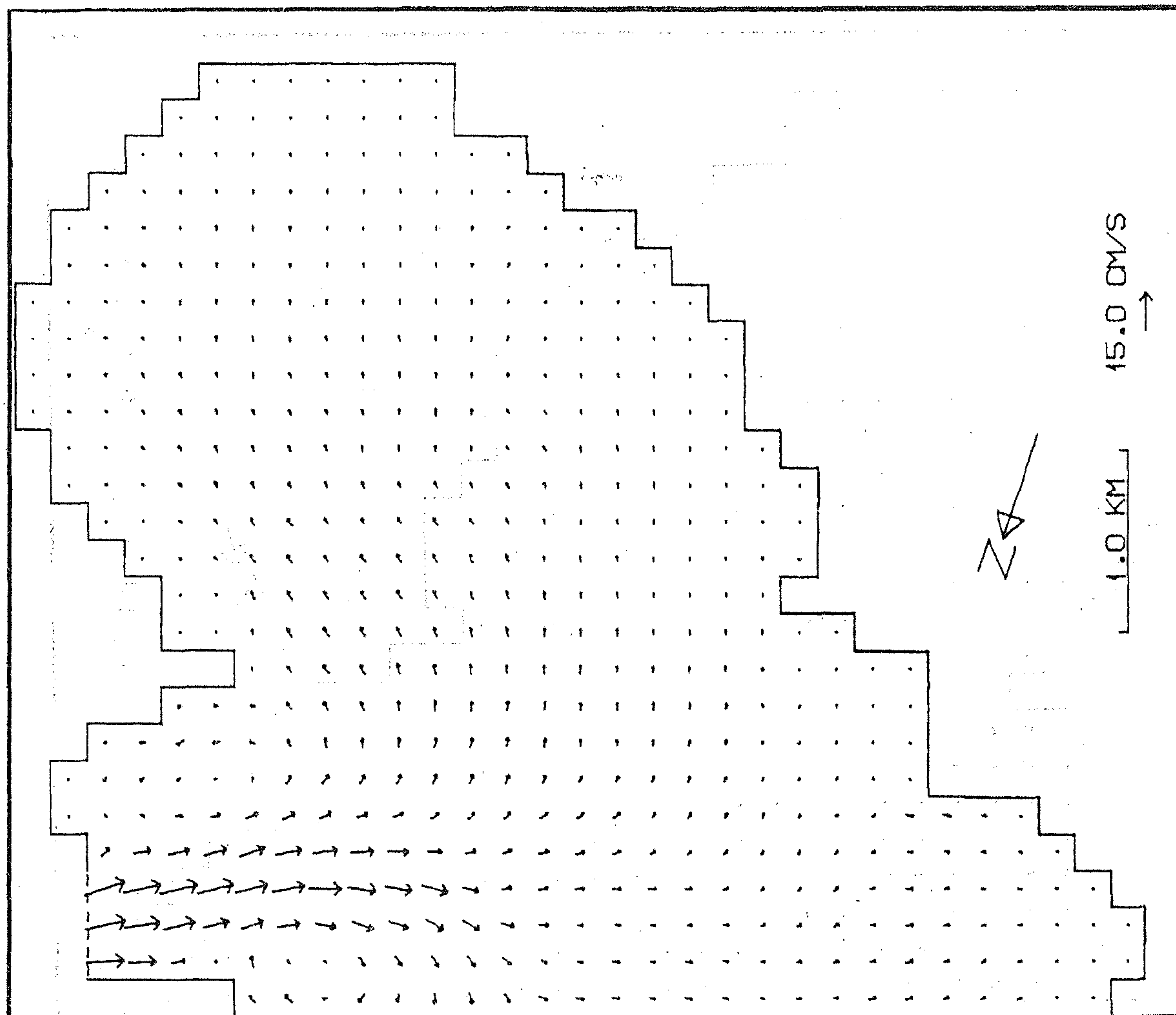

Figure 5: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water + 9 hours.

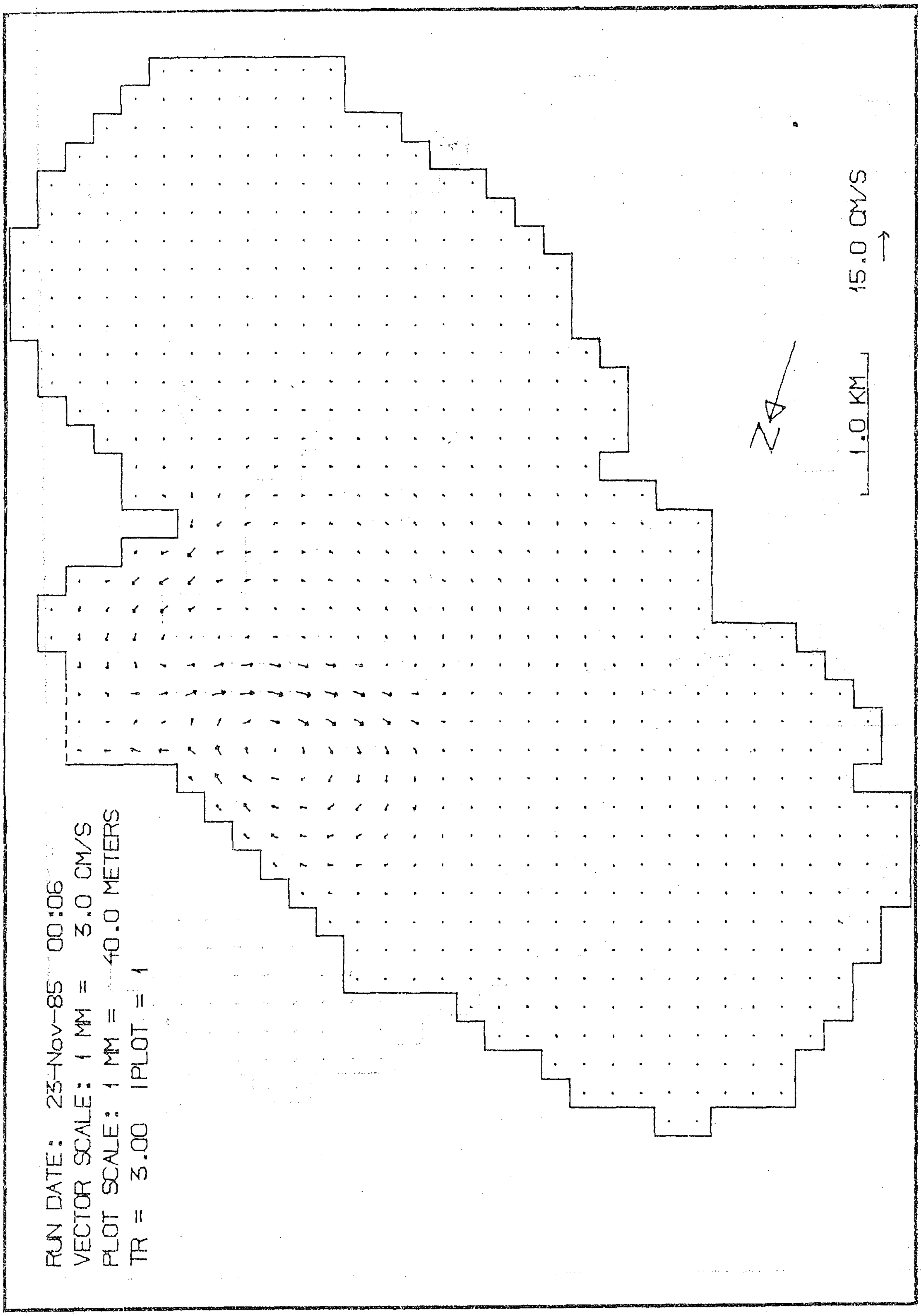

Figure 6: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water + 12 hours.

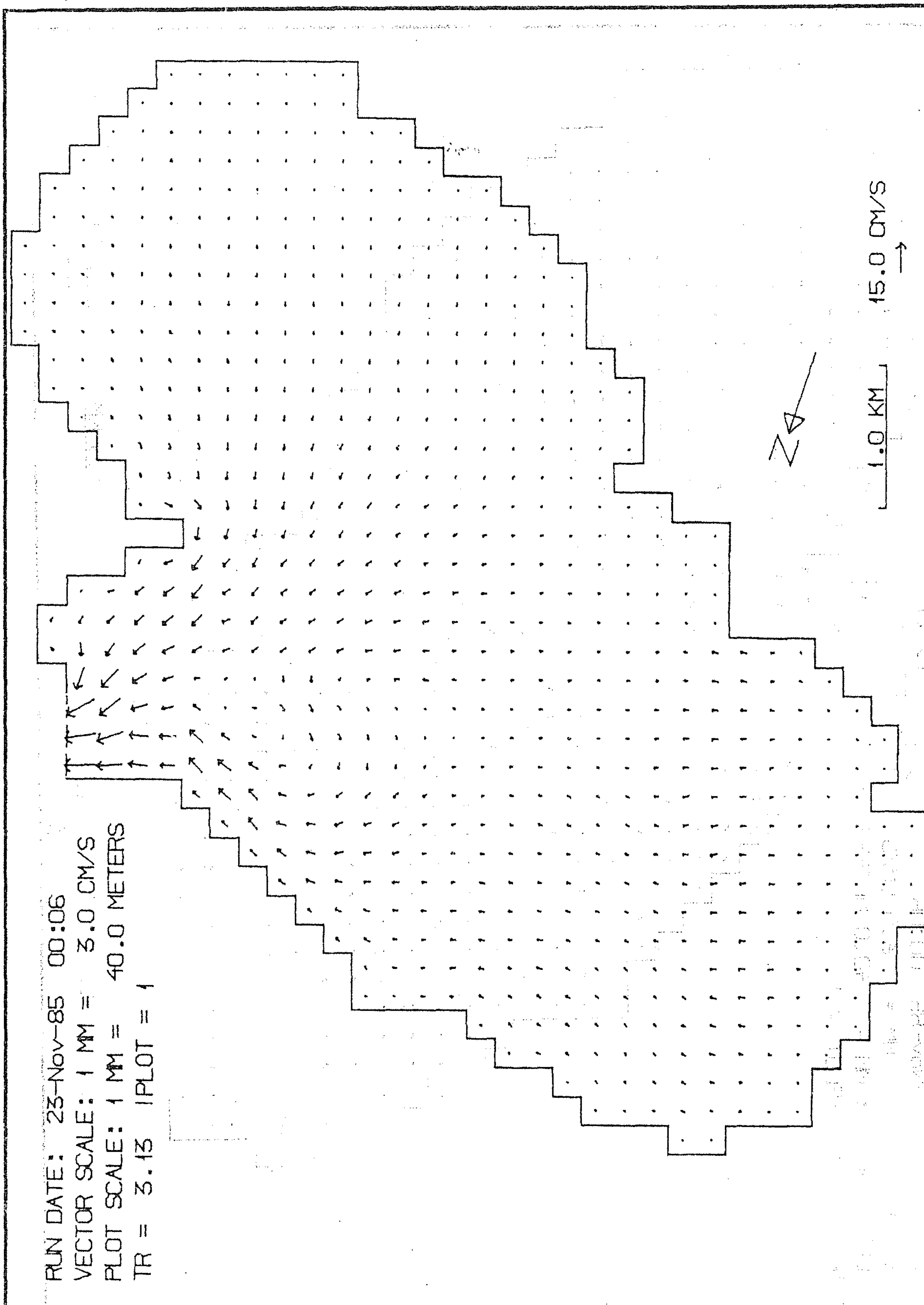

Figure 7: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water + 15 hours.

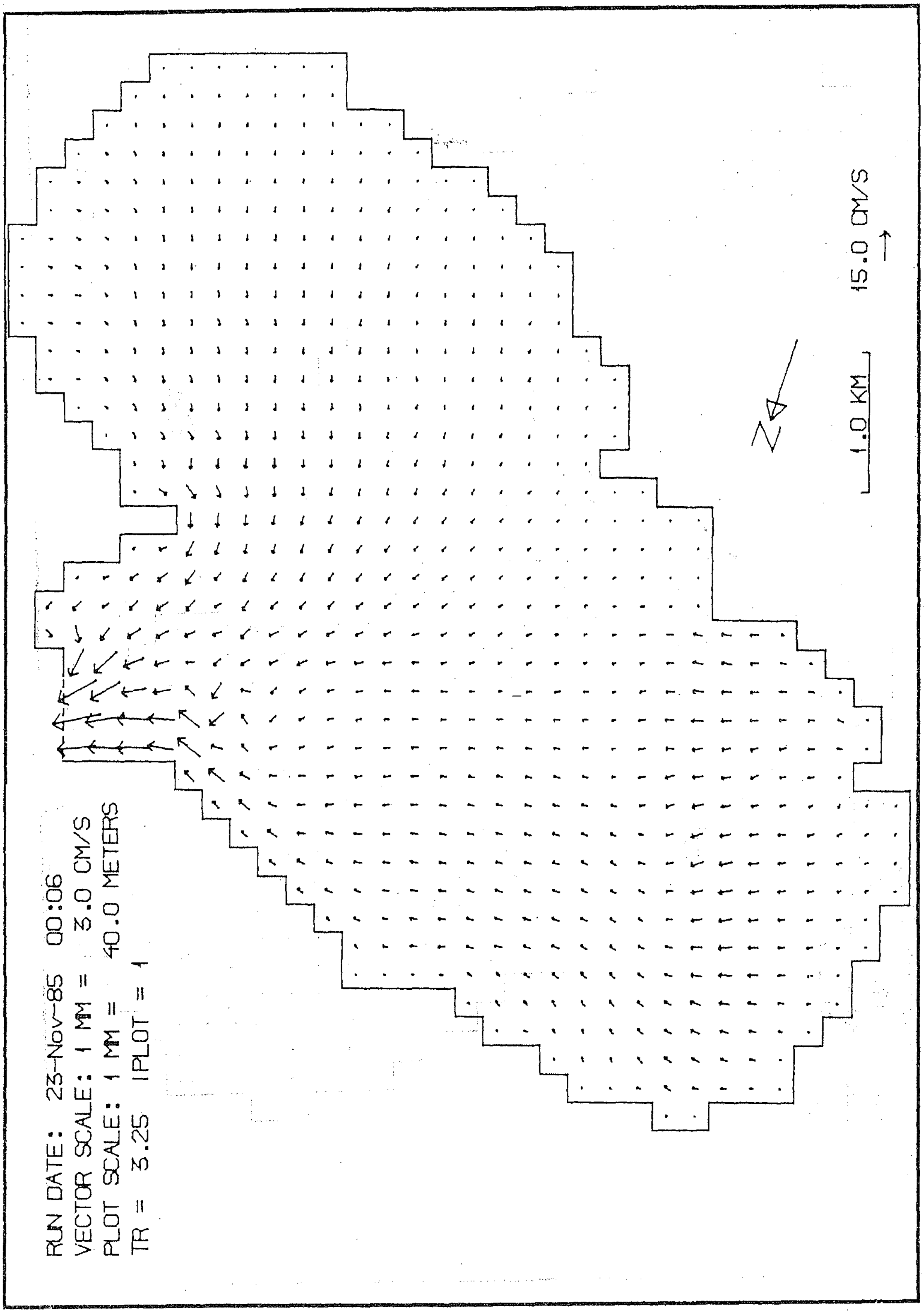

Figure 8: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water + 18 hours.

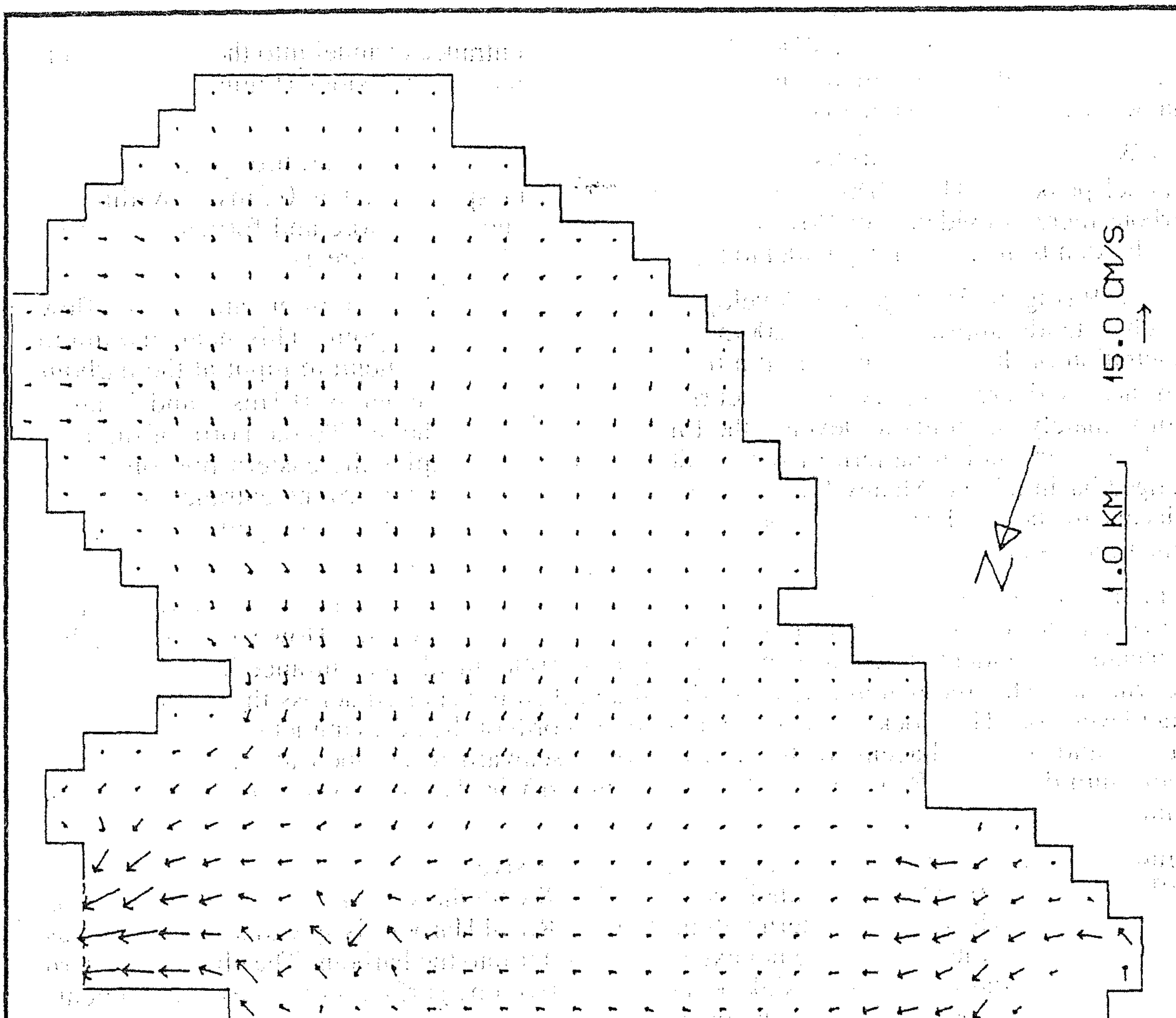

Figure 9: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m; time of Low Water + 21 hours.

Three hours after low water (LW+3) the flow from the entrance channel into the harbour tends to fan out radially and remains attached to the coastline on both sides (Figure 3) which is characteristic of a hydrodynamic volume source flow.

At LW+6, as the water surface rises through its mean level, flow rate through the entrance channel peaks ($1.04 \times 10^3 m^3 s^{-1}$) and channel current speed reaches $0.3 ms^{-1}$. Within the harbour there is evidence of flow separation from the northern shore and formation of a jet which extends in a direction parallel to the entrance channel axis (Figure 4).

At LW+9 (Figure 5) the jet has developed into a well-defined region of enhanced axial flow which extends approximately 2200m into Princess Royal Harbour. This near-maximum penetration of the jet is achieved at a time when the rate of momentum input at the harbour entrance is decreasing. A typical current speed within the jet is $0.1 ms^{-1}$ and it takes approximately six hours to develop the full spatial extent of the jet. To the north of the jet a clockwise circulation pattern of 600 to 800m diameter occupies the eastern portion of the dredged basin off the Albany Port Authority wharfs, with flow toward the entrance occurring adjacent to these wharfs. South of the jet, an anti-clockwise eddy flow pattern of similar dimensions occurs.

At high water (LW+12) the flow rate through the entrance is again momentarily zero. Figure 6 shows that current speeds adjacent to the harbour entrance are low. However considerable momentum is evident at distances between 700 to 2500m inside the entrance in the form of a decaying jet. This momentum was introduced and then transported across the harbour as the water level rose. The clockwise eddy pattern to the north of the decaying jet (diameter 1600m) persists and water adjacent to the wharfs moves seaward to compensate for the remnant momentum-driven jet. Recirculating flows also intensify in shallower water north-east of Geak Point.

Figures 7, 8 and 9 show the velocity fields at successive stages of the falling tide. Strong outflow through the entrance channel peaks at LW+18 with the same flow rate and velocity as for peak inflow. The outflow pattern within Princess Royal Harbour is spread angularly and as a consequence elevated speeds are not experienced so far into the harbour. The ebb flow pattern resembles potential flow about a sink because it is driven by surface slope pressure gradients induced by volume outflow and not by the transport of momentum.

At LW+15 (Figure 7) the remnants of the tidal jet and the clockwise eddy to its north can still be seen in an area between 1200 to 2200m inside the harbour entrance. The water in these flow features has not yet been accelerated to a seaward direction. Most of the outflowing water is derived from two areas; the eastern port area and to the south of Geak Point. Between these two areas, some inward directed momentum from the flood jet still remains. Hence, the influence of the flood tidal momentum injection remains significant for about three hours after high water, whereas the influence of ebb tide and water extraction virtually ceases at low water.

At LW+18 and LW+21 (Figures 8 and 9) there is a seaward current throughout the harbour.

The field of net transport velocity resulting from a complete tidal cycle was calculated by the model and is shown in Figure 10. The net transport velocity is defined at any given plan location in the harbour as the tidal average of the local depth-integrated volume flux, divided by the tidal average of the local water depth. Areas of significant net transport velocity reflect the flow-dominance of the inward-directed tidal jet, and of the clockwise recirculating eddy adjacent to the Albany Port Authority wharfs. A characteristic length for the tidal jet was defined as the length along the jet axis from the harbour entrance to a point where the tidally-averaged transport velocity has a value equal to 10 per cent of the average tidal speed at the harbour entrance. A value of 2100m was derived from Figure 10. This is the distance inside the harbour entrance to which there is jet-induced flow-dominance. This approach also highlights the flow-dominance of two recirculation features, one to the north and one to the south of the axis of the tidal jet. The northern recirculation feature in deeper water is stronger and smaller than the southern recirculation feature.

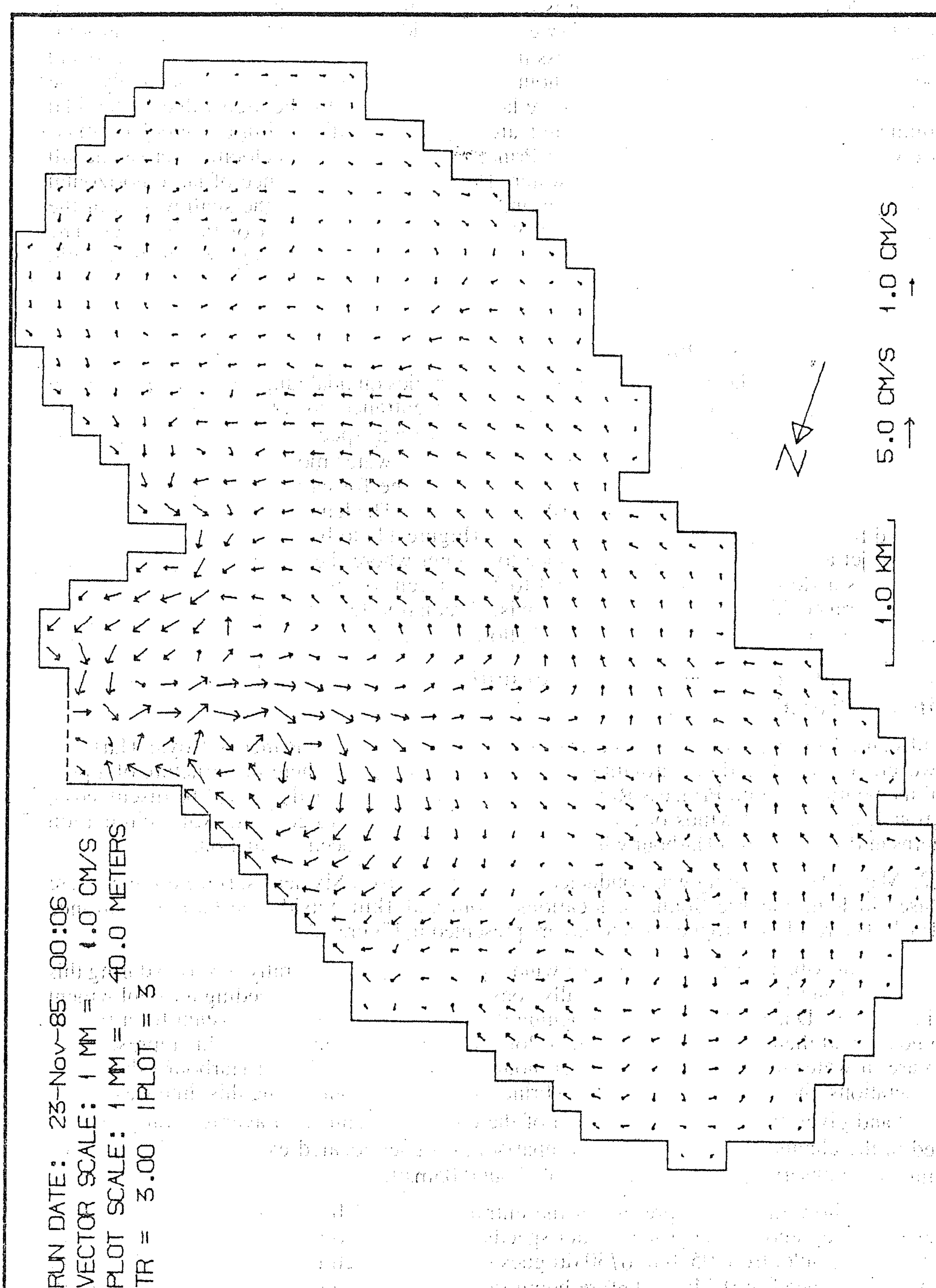

Figure 10: Modelled net (tidally-averaged) transport velocity distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m.

The main Princess Royal Harbour basin is bordered to the north-west by a very shallow sill which forms the outer part of the north-western intertidal to subtidal shelf of the harbour. Figures 5 and 7 show that tidal flows across this sill can be strong (~ $0.12 ms^{-1}$). Peak ebb and flood speeds occur about two and a half hours before and after low water, respectively. The speed and timing of these peak velocities are largely influenced by the high value of the tidal amplitude to mean water depth ratio and are consistent with a simple model of mass conservation across the north-west shelf of Princess Royal Harbour. Velocities across the sill are very small at times of low and high water. This suggests the absence of large horizontal gradients of water level across the harbour and indicates that despite the shallowness of the western margin its water level remains in phase with that of the rest of the harbour. The maximum extent of drying at LW shown in Figure 2 is generally in agreement with field observations.

3.1.2 Diurnal tide of range 0.7m

In order to investigate the dependence of flow characteristics on tidal range the numerical model was re-run for a tidal range of 0.7m. At the harbour entrance, average volume influx was $463 m^3 s^{-1}$ average current speed was $0.13 ms^{-1}$ and average specific momentum influx was $77 m^4 s^{-2}$. The model results described a similar cycle of water movement patterns to those discussed above, i.e. jet development and decay, with the formation of side-eddy features during flood tide and more angularly distributed ebb flow. The length scale of the tidal jet was estimated from the field of net transport velocity (Figure 11) to be 1950m. This is the length along the jet axis from the harbour entrance to a point where the tidally-averaged transport velocity has a flood-dominant value equal to 10 per cent of the average tidal speed at the harbour entrance. The flow-dominant clockwise circulation feature in the port area was less extensive. The peak current speed over the shallow western sill was $0.045 ms^{-1}$.

3.2 Drogue tracking measurements of tidally-induced flow in Princess Royal Harbour

A substantial programme of drogue tracking was conducted in Princess Royal Harbour. However, very rarely did this droguing occur in calm conditions where the structure of a pure tidal momentum jet into Princess Royal Harbour could be examined. As will be discussed in Section 4.3, even light winds of a few hours duration are able to generate water circulation patterns in Princess Royal Harbour which modify the tidally-induced circulation.

On 23 May, 1985, droguing was conducted from 0316 to 1017. Six near-surface drogues were released in King George Sound at locations 500m and 1km outside the harbour entrance channel. The resulting drogue trajectories are presented in Figure 12.

Recordings at Albany airport indicate that winds were very light (generally $0\text{-}3 ms^{-1}$) during this period. The water level remained essentially constant for three hours preceding the deployment of the drogues. During the period of droguing the water level remained constant for a further two hours, and then rose (from 0.54m to 1.26m) between 0500 and 1200. This represents an increase in water level of 0.72m in seven hours. From Princess Royal Harbour tidal prism considerations, the water volume flux into Princess Royal Harbour during this time was $2.07 \times 10^7 m^3$ and given the cross-sectional area of the entrance channel, an average water current speed in the channel is $0.23 ms^{-1}$. By comparison, drogues located external to the entrance channel were observed to move at speeds of about $0.05 ms^{-1}$.

These data show that water present in the entrance channel between 0530 and 1015 was accelerated well above background water speeds and jetted into the Princess Royal Harbour basin. For example, from 0530 to 0730 drogues #1 and #3 penetrated 1750m into the harbour at an average speed of $0.24 ms^{-1}$ before being retrieved. At about 0900, drogues #2 and #10 moved into the harbour at $0.14 ms^{-1}$. Each of these vigorous penetrative flows within Princess Royal Harbour was directed parallel to the central axis of the entrance channel and was characteristic of a momentum jet. The penetration distance of flooding water was much greater than measured by the drogues, because of the limited duration of drogue deployment. The

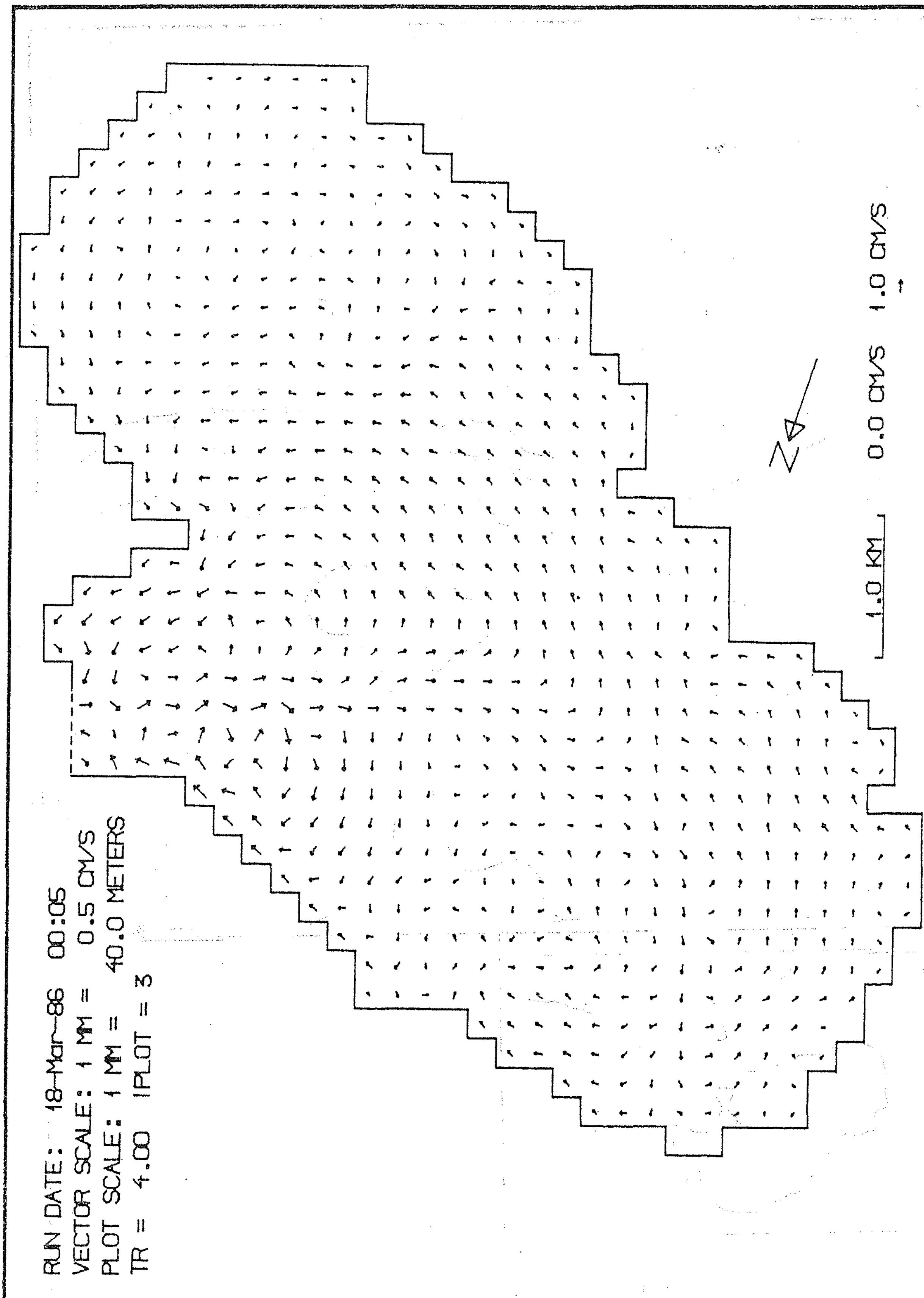

Figure 11: Modelled net (tidally-averaged) transport velocity distribution in Princess Royal Harbour, subject to a diurnal tide of range 0.7m.

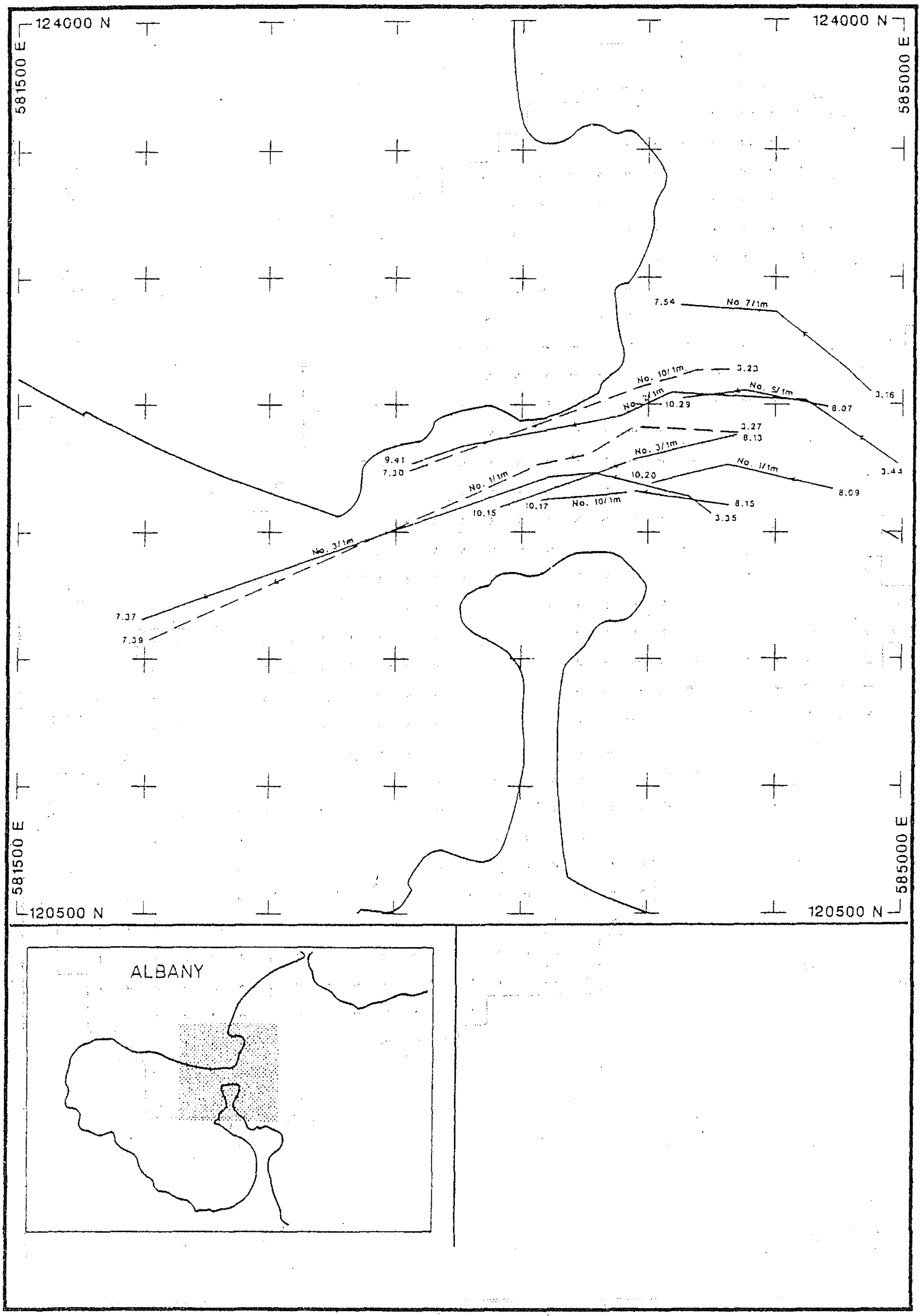

Figure 12: Drogue trajectories in King George Sound released within 1km of the Princess Royal Harbour entrance during a flood tide and light wind conditions on 23 May 1985, 0316-1017

presence of vortices associated with the tidal jet were not confirmed by this drogue deployment, possibly because of the sparcity of drogue observations within the harbour. The radius of abstraction of water from King George Sound appears to be of order of 1000m. Drogue #2, released at this distance outside the entrance channel, entered Princess Royal Harbour after 5.5 hours moving at an average speed of $0.08ms^{-1}$. Given the Princess Royal Harbour tidal prism and typical depths of about 10m in King George Sound adjacent to the channel, this result is consistent with a radial inflow toward the channel.

3.3 The dynamics of tidally-induced flow in Princess Royal Harbour

The nature of the force balance governing tidal motion in Princess Royal Harbour was examined. Generally, the dynamic balance was found to be complex and variable with location in the harbour. Local fluid acceleration, inertia (momentum advection), Coriolis force, pressure gradient force and bottom friction force can all be of importance.

Flow through the entrance channel is driven by water surface slope and therefore tends to be uni-directional from surface to the bottom. A tidal range of 0.5m gives rise to an average current speed at the harbour entrance of $0.1ms^{-1}$. Within the harbour near the entrance, for current speeds greater than about $0.1ms^{-1}$, the fluid inertia is more important than the pressure gradient force. Thus for tidal ranges in excess of 0.5m the inflow resembles jet flow rather than more distributed potential flow from a source. The water depth decreases along the axis of the jet flow into Princess Royal Harbour. The momentum jet is therefore not expected to separate from the harbour bottom and the influence of bottom friction is important. The time scale for jet development, defined as maximum jet length divided by a typical axial jet speed, is about six hours compared with a typical 12 hours of inflow and therefore the jet flow is unsteady. The asymmetric flow pattern associated with a flood jet and radial ebb flow at high tidal ranges is likely to promote greater water exchange than the weaker, more reciprocal potential flow patterns caused by low tidal ranges.

The specific momentum influx, which drives Princess Royal Harbour tidal jet flow, varies roughly as the square of the tidal range. It is noted however, that the length scales of the tidal jet are somewhat insensitive to variations in the tidal range. The two model runs indicate jet lengths of 1950m and 2100m corresponding to tidal ranges of 0.7m and 1.0m, respectively. This insensitivity is consistent with a simple inertia-bottom friction balance for a jet, although in Princess Royal Harbour other dynamic factors are also present.

Away from the entrance and the tidal jet (when it exists) the major influences on the flow are the pressure gradient force and the bottom friction. The Coriolis force is non-negligible throughout.

Comparison of current speeds over the shallow sill bordering the outer edge of the north-western shelf of Princess Royal Harbour illustrates a strong dependence on the tidal range. This is consistent with a one dimensional model of tidal flow onto a shallow shelf which shows that peak current speed at the outer edge of the shelf varies more than linearly with tidal range and confirms that the magnitude and timing of these peaks depend on the tidal amplitude to mean water depth ratio.

The net transport fields (Figures 10 and 11) indicate the extent and importance of the tide (for tidal range > 0.5m) as an agent of internal circulation and mixing. Although these hydrodynamic model results are suggestive of mechanisms of water exchange, it is not possible to evaluate flushing without recourse to a Lagrangian description of the flow which provides actual water trajectories. The trajectories of water depend on both the spatial and temporal variability of the Eulerian flow field of the harbour. Such a Lagrangian technique is applied in Section 5.

4. Flow in Princess Royal Harbour induced by wind and tide

The waters of Princess Royal Harbour are generally influenced by wind and tide simultaneously. This section analyses the relative influence on the circulation of these two forcing factors, examines some of the typical circulation patterns which can result from the combined forcing and the potential for water exchange between Princess Royal Harbour and King George Sound under these conditions. The hydrodynamic model is used and model results are compared with field data.

4.1 Numerical simulation of flow in Princess Royal Harbour induced by wind and tide

4.1.1 Diurnal tide of range 1m, and north-west wind of 7.5ms^{-1}

The hydrodynamic model was used to investigate water movements in Princess Royal Harbour due to a combination of wind and tidal influences. The model was forced by applying:

- a steady wind stress of 0.1 Pa to the south-east, uniformly distributed across Princess Royal Harbour (corresponding to a steady north-west wind of 7.5ms^{-1}) and
- a specification of volume flux across the model open boundary (harbour entrance) corresponding to a diurnal, sinusoidal tide of range 1m, as used in section 3.1.

Anti-clockwise wind-driven circulation in Princess Royal Harbour is clearly apparent at the time of low water (Figure 13) when momentarily, there is no water mass or momentum flux across the harbour entrance. Water movement in the port area is to the north-west, parallel to the wharf edge. West of the port area the water is mainly deflected around an intertidal to subtidal margin. The current is directed down-wind over shallow water adjacent to the south-west shore of Princess Royal Harbour and recirculates via the central and south-eastern parts of the harbour. There are two shallow areas where small clockwise circulations persist. They are, an area of about 0.5km^2, situated between Frederick Point and Melville Point and the south-east area known as Shoal Bay. On the north-western shallow margin, flow is strong over the outer edge however, the exposure of about 0.9km^2 of intertidal sand bank temporarily blocks flow over the inner part of this margin. Throughout the whole of Princess Royal Harbour there is approximately 1.5km^2 exposed at low water.

Figures 14, 15 and 16 represent the fields of water movement at times three, six and nine hours after low water. Water entering the harbour during the initial stages of the flood tide is directed south-west and remains attached to the coast between Bramble Point and Geak Point. North-west of Geak Point the inflowing water is deflected to the right as it merges with the general wind-driven, anticlockwise circulation of Princess Royal Harbour. As the water surface continues to rise (through mean sea level) water flow into Princess Royal Harbour progressively aligns itself to be more parallel with the axis of the entrance channel and penetrates further into the harbour prior to being forced to the right by the wind-driven circulation. An eddy is initiated near the deep water jetty as a result of flow separation from the northern shore. This eddy subsequently elongates in a direction parallel to the wharf front and the features of a flood tidal jet emerge as flow separation from the southern coast also occurs. Generally, the combined effect of the wind and flood tidal action is to reinforce inward directed flow in the northern part of the Princess Royal Harbour and to weaken flow and disrupt flow patterns south-west of Geak Point where there is an area of almost stagnant water.

At time of high water, a complete anti-clockwise wind-driven gyre (augmented by previously introduced tidal momentum) again becomes apparent (Figure 17); the water mass and momentum flux across the entrance to the harbour are momentarily absent. The recirculation feature adjacent to the deep water jetty and the wharfs has evolved to about its maximum extent

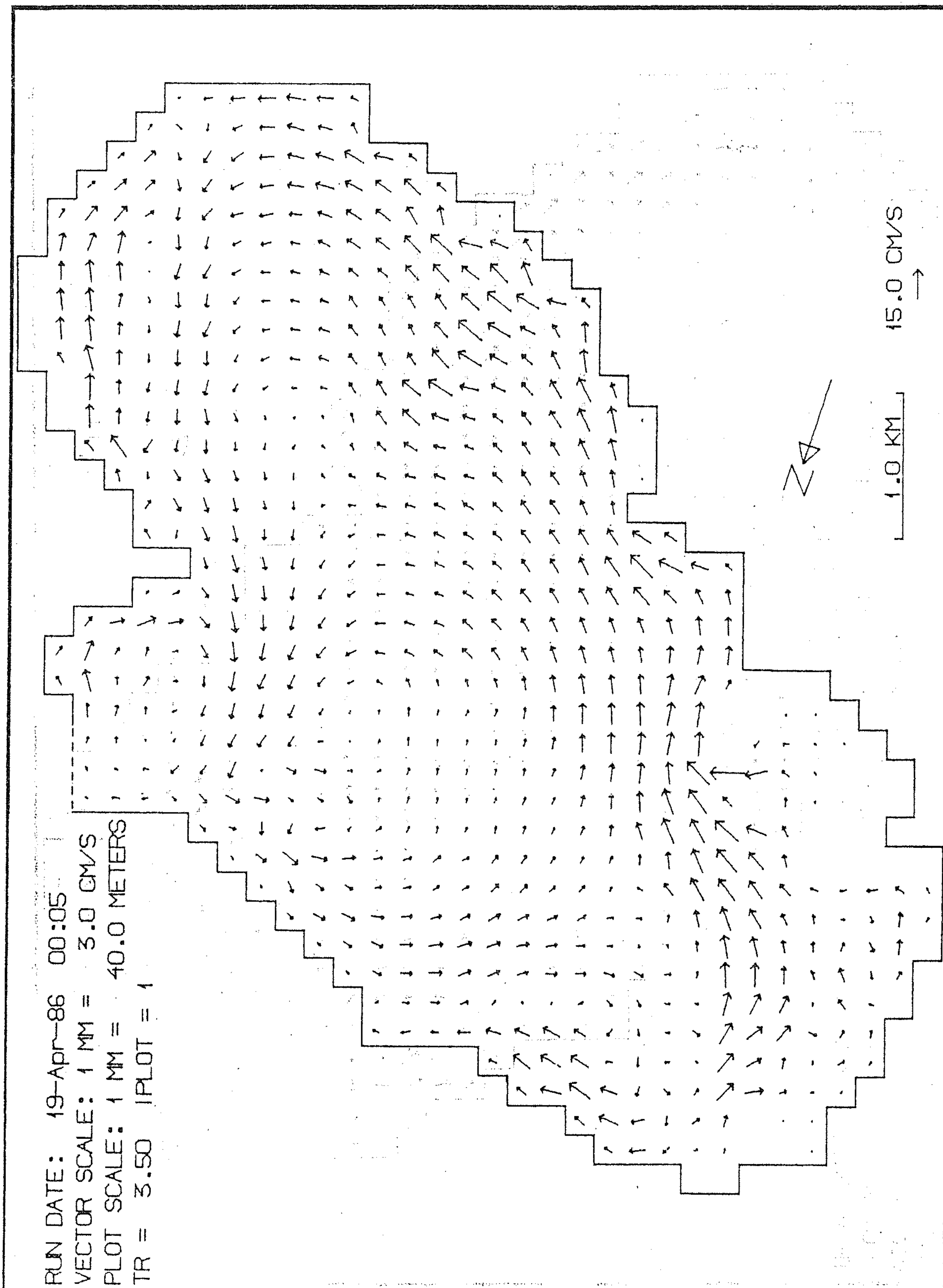

Figure 13: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water.

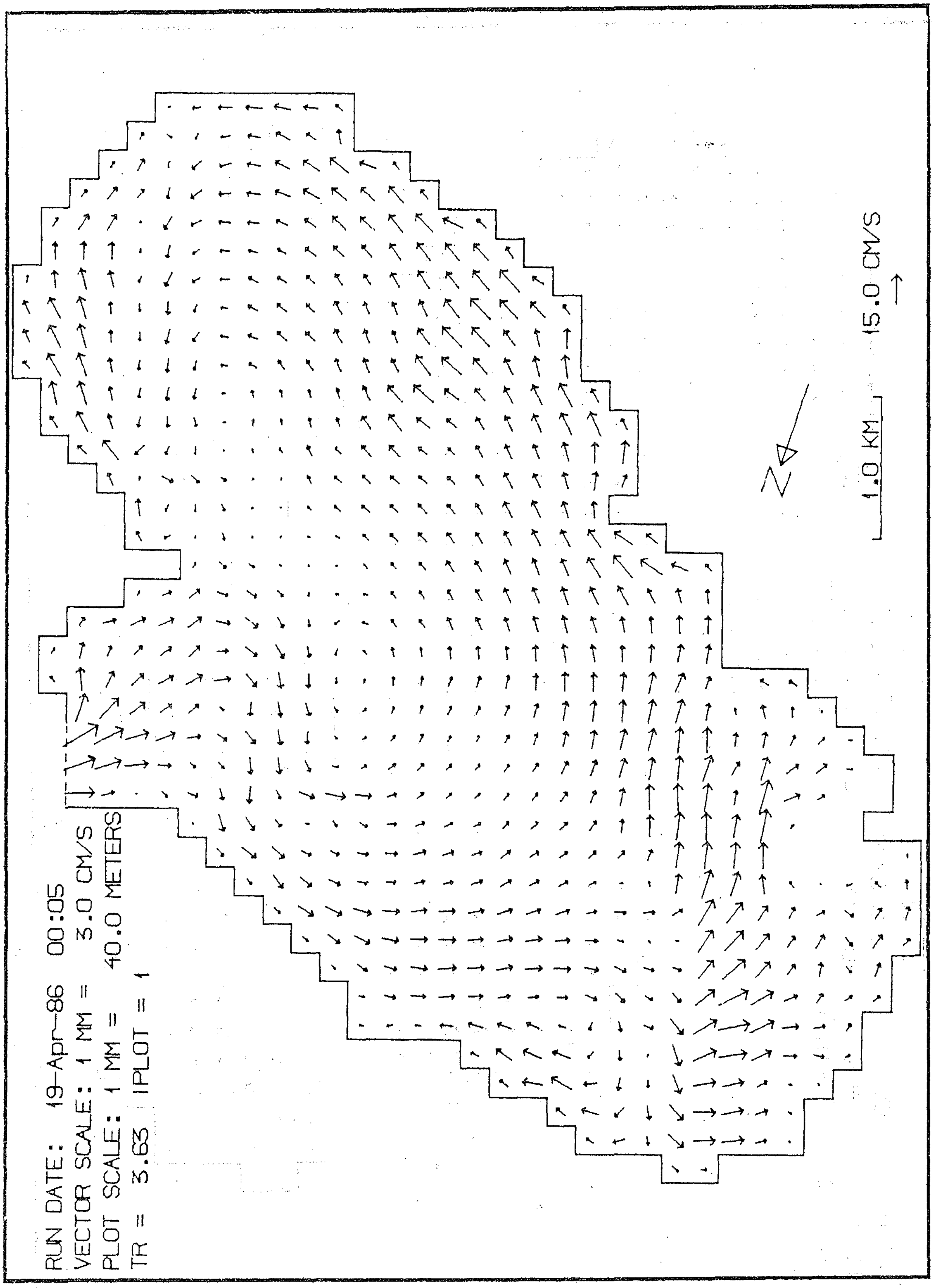

Figure 14: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water + 3 hours.

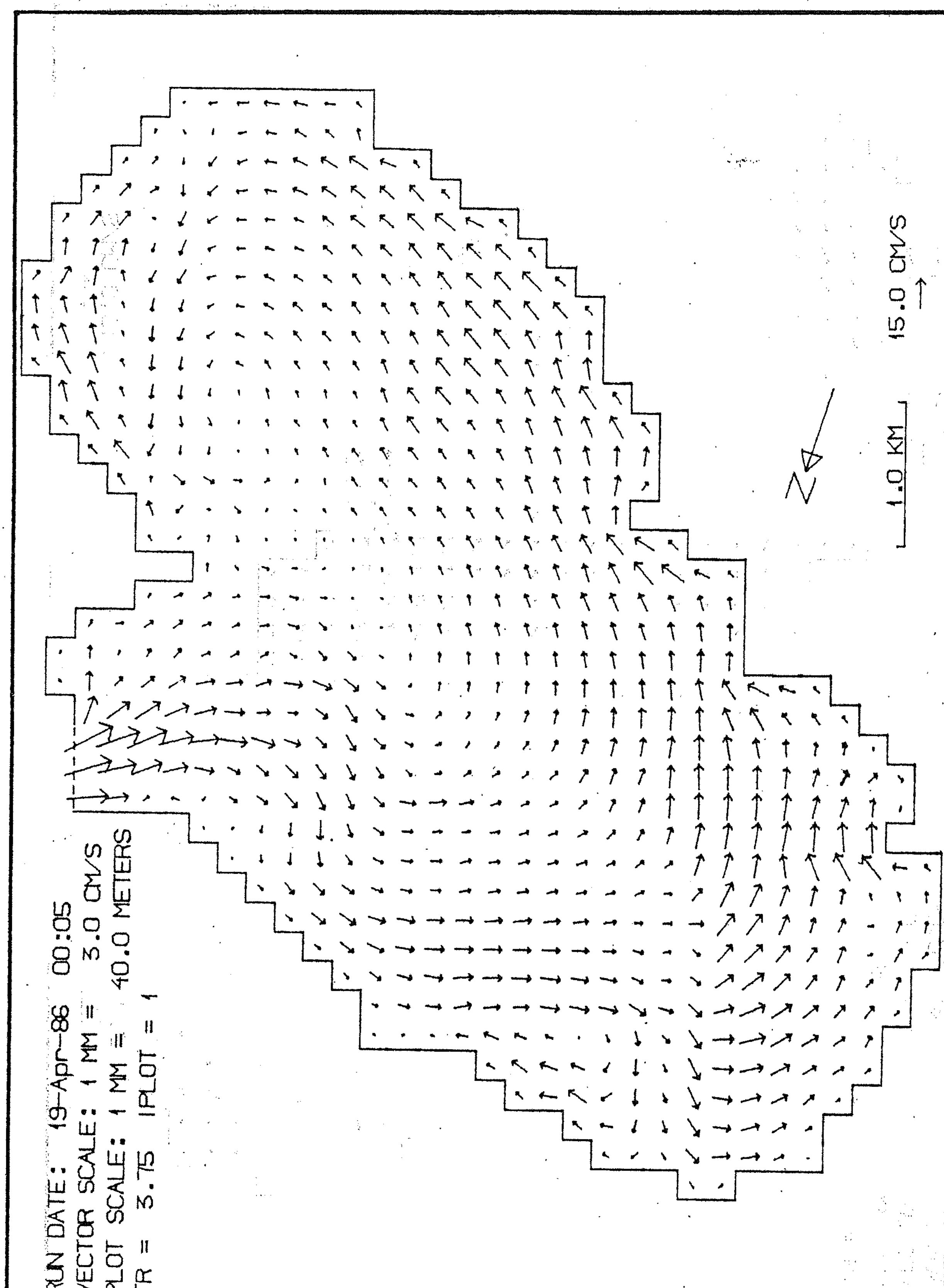

Figure 15: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water + 6 hours.

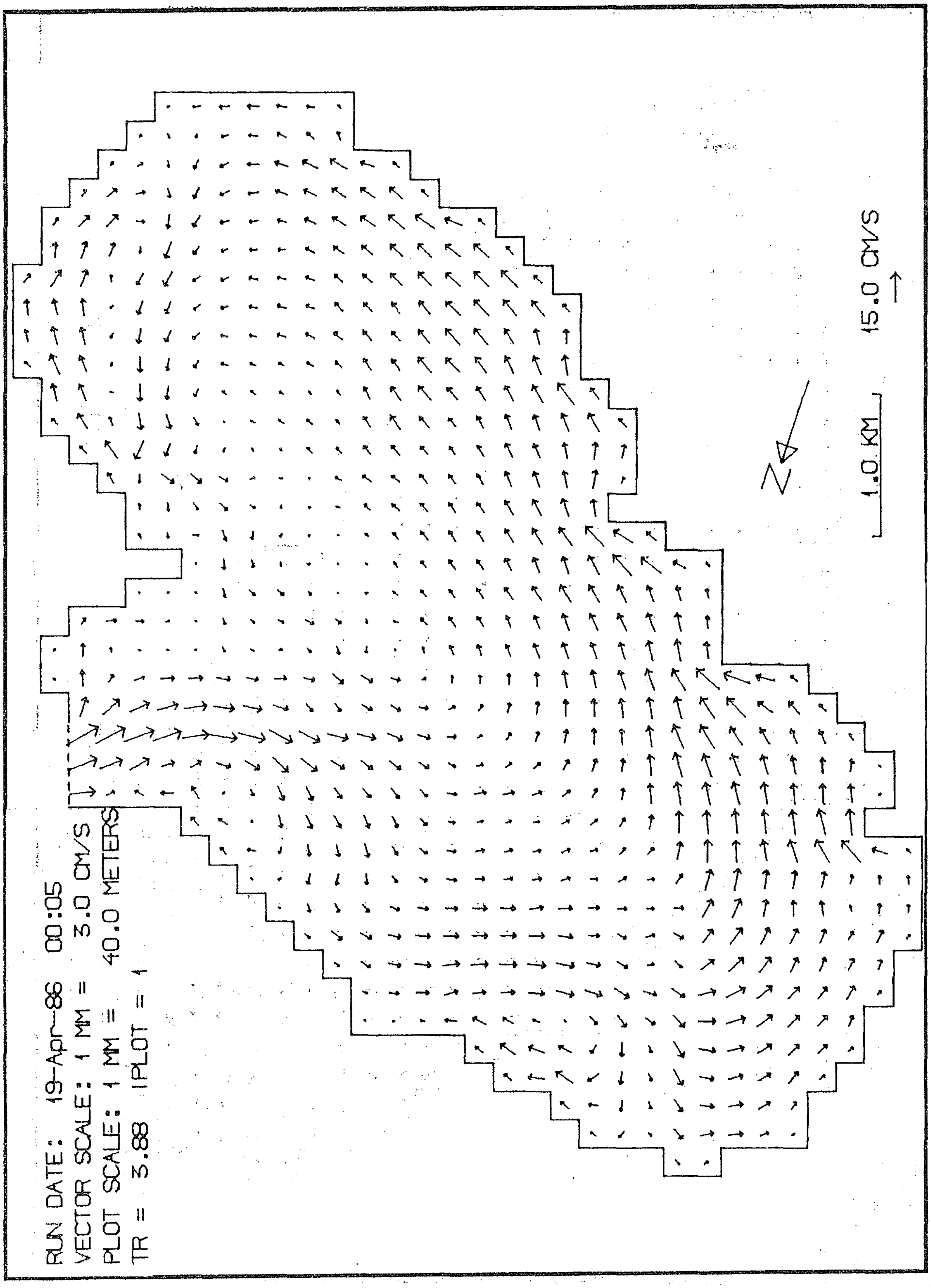

Figure 16: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water + 9 hours.

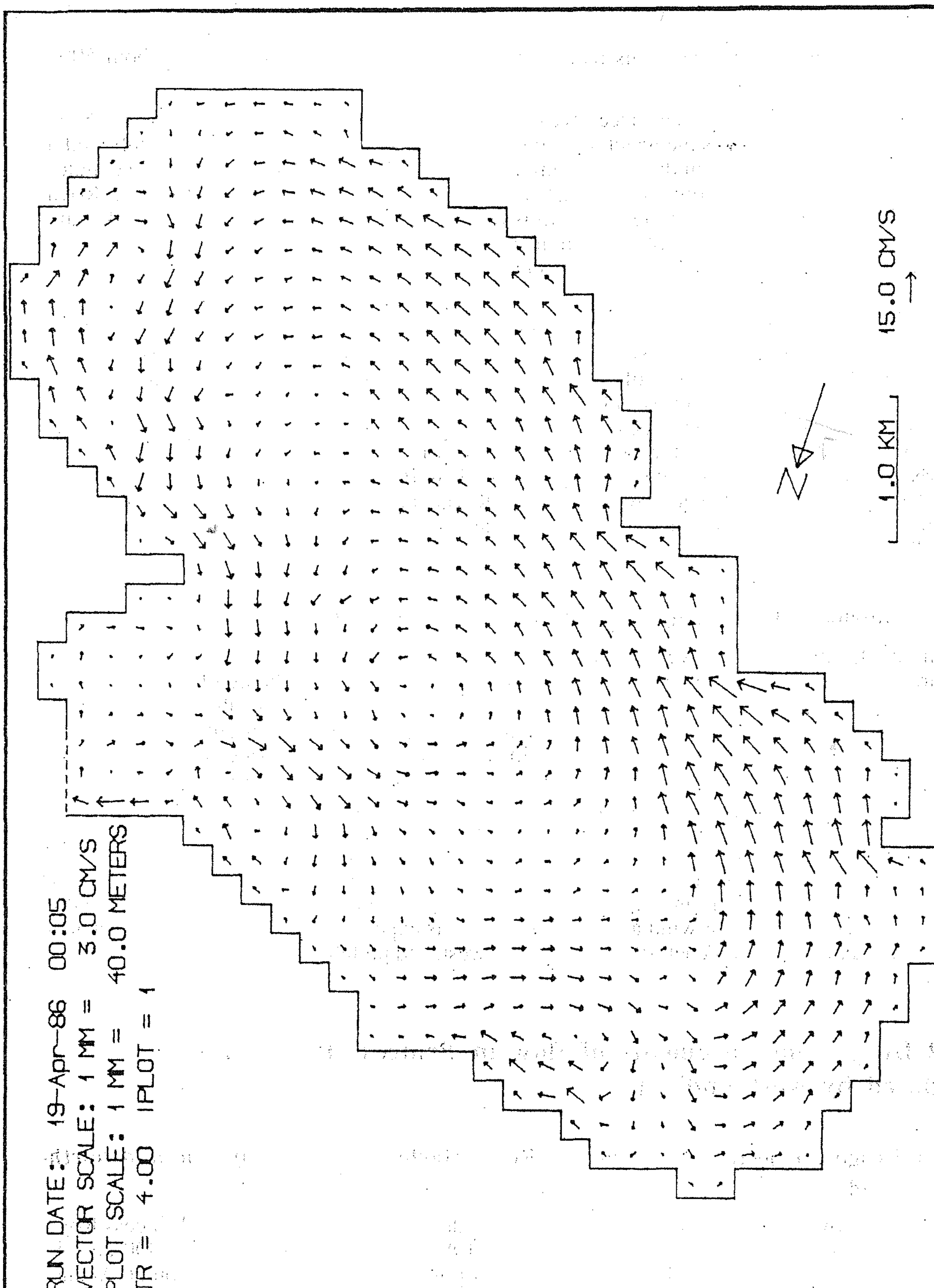

Figure 17: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water + 12 hours.

(800m along the wharf face). This feature displaces the inwards directed flow about 500m offshore.

Figures 18, 19 and 20 show the successive distributions of water current velocity at 15, 18 and 21 hours after low water as the water level falls. It is seen that the flow speeds are reinforced to the south-west of Geak Point due to the cumulative effect of ebb tidal currents and the counter-clockwise wind-driven flow. In contrast, an area in the northern part of Princess Royal Harbour with water depths greater than 2m is characterised during this period by weak water movement. Inward movement of water in the port area, which would normally occur under the influence of north-west winds alone, is limited. In the latter stages of the ebbing tide areas of intertidal banks are uncovered.

In summary, it can be seen that water entering Princess Royal Harbour during the flood tide is deflected to the right (north-west) as it comes under the influence of the counter-clockwise wind-driven circulation. Some of this water is able to penetrate sufficiently far along the northern shore of the harbour as to be beyond the area of strongest water withdrawal during ebb tide. This water therefore does not greatly change its position as water level falls. Water leaving the harbour during the ebb tide is drawn principally from central Princess Royal Harbour and the area immediately south-west of Geak Point. These model results illustrate a mechanism of water exchange between Princess Royal Harbour and King George Sound which operates under conditions of steady, moderate, north-west winds and near-spring tidal conditions.

4.1.1 Diurnal tide of range 1m and south-east wind of 7.5ms^{-1}

Mills and Brady (1985) showed that south-east wind acting on Princess Royal Harbour sets up a large clockwise circulation gyre in the harbour, the circulation flux being of the same order, but reversed in direction to that for north-west wind. Based on the results of the previous section, the interaction of this clockwise wind-driven circulation with circulation induced by tidal flow through the entrance can be anticipated as follows. As the water level rises, water flowing into the harbour will merge with the general wind-driven circulation. Inflowing waters will therefore be deflected to the left and will move initially in a south-west to south direction with little water penetration into the deep turning basin adjacent to the north shore of the harbour where currents are expected to be weak. About the time of high water, complete clockwise circulation should be present within the harbour, and during falling water level the waters exiting the harbour are expected to be drawn predominantly from the northern shore. Again, this combination of wind and tidal conditions is expected to favour net water exchange but with maximum flood penetration to the south-west, and preferential ebb flow adjacent to the north shore.

4.2 Drogue measurements of flow in Princess Royal Harbour induced by wind and tide

4.2.1 Drogue trajectories in Princess Royal Harbour induced by tide and north-west wind

Figure 21 shows the trajectories of eight drogues released near the entrance of Princess Royal Harbour between 1700 and 1745 on 25 August 1985. Low water occurred at 1800 and the water level subsequently rose by 0.6m till the end of the drogue tracking at 0240 on 26 August. The full tidal range was 0.8m. The wind, as measured at Albany Airport, had an average speed of 6-7ms^{-1} during the period of drogue tracking and its direction was predominantly in the range 280-340° north. The wind had been blowing consistently from these directions for eight hours prior to the commencement of droguing. Within the harbour entrance channel drogue speeds of about 0.25ms^{-1} were registered. This is consistent with calculated mean current speeds through the entrance channel based on the rate of water level increase and the volume of

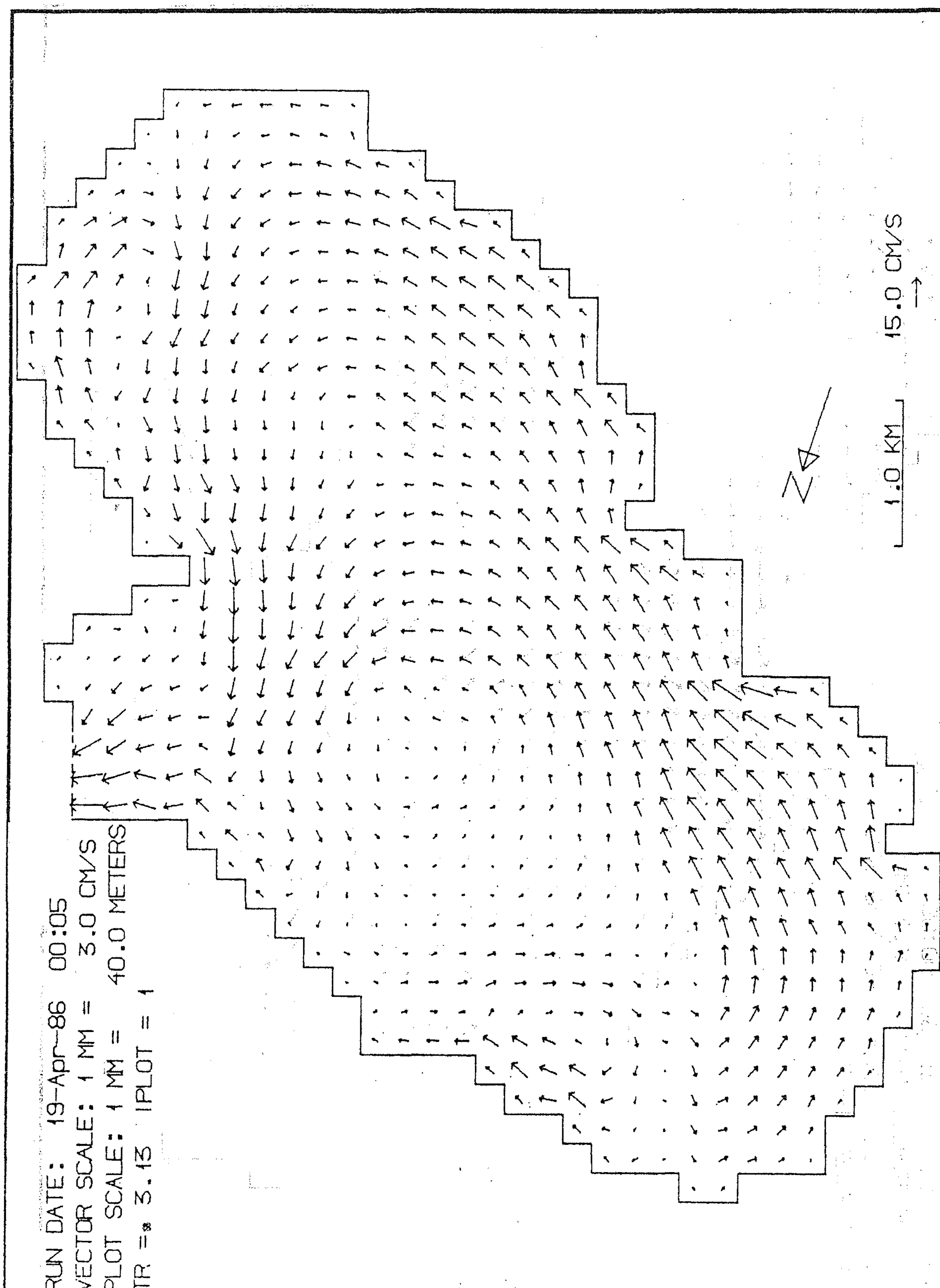

Figure 18: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water + 15 hours.

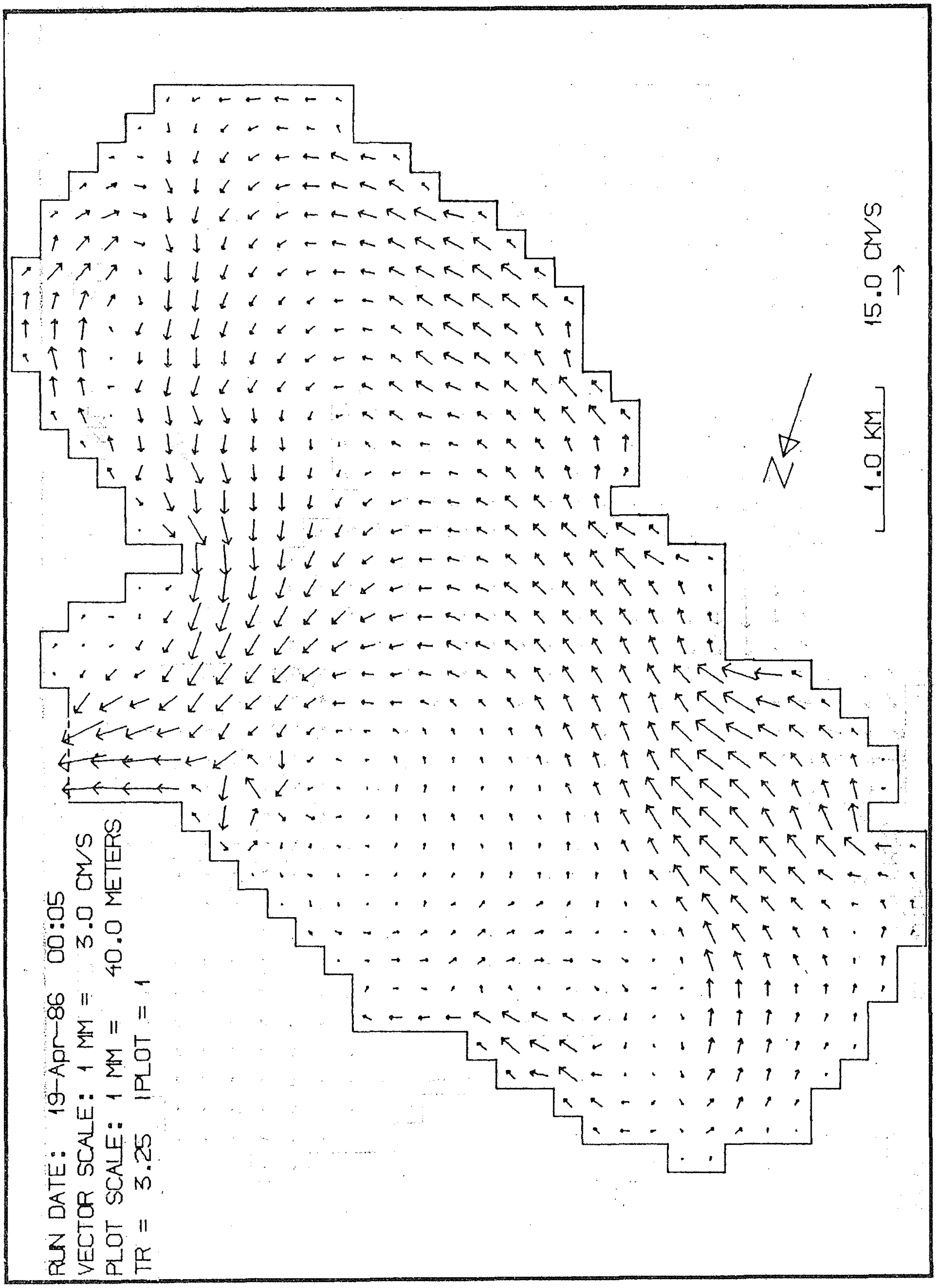

Figure 19: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water + 18 hours.

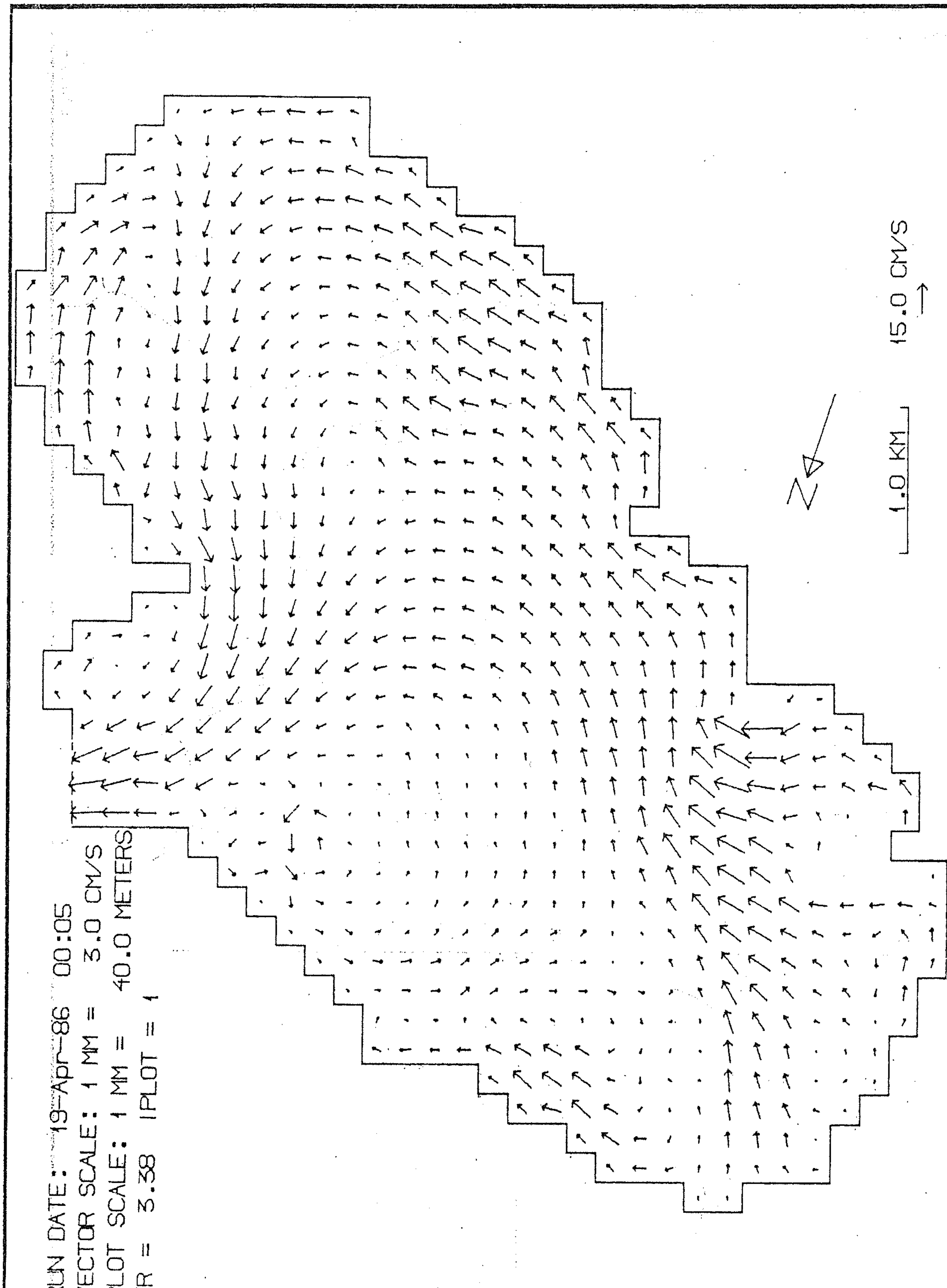

Figure 20: Modelled, instantaneous water current distribution in Princess Royal Harbour, subject to a diurnal tide of range 1m and northwest wind of 7.5 ms^{-1}; time of Low Water + 21 hours.

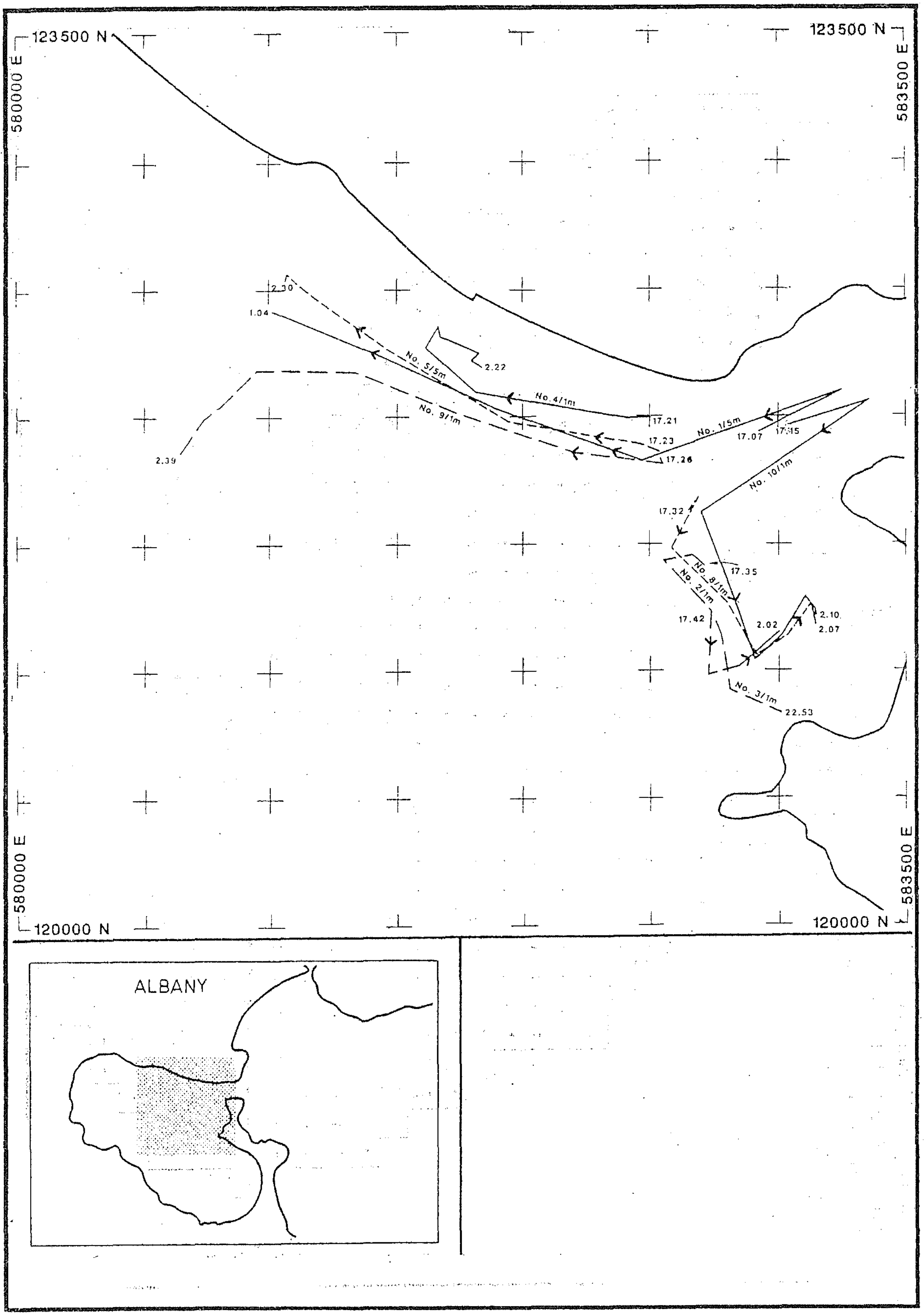

Figure 21: Drogue trajectories in Princess Royal Harbour induced by tide and north-west wind; 25-26 August 1985, 1700 to 0240

the Princess Royal Harbour tidal prism. Figure 21 shows that the drogues separated into two groups of four.

One group, comprising drogues #4 and #9 (1-3m below the surface) and drogues #1 and #5 (5-7m below the surface), deflected to the right of the entrance channel axis alignment and moved up to 2000m into the harbour, roughly parallel with the port wharfs. Two of these drogues ran aground in shallow water four hours before HW hence, the actual water excursion into Princess Royal Harbour was greater than that indicated by the drogue movements. These data confirm that the inflow extends throughout the the major portion of the water column. The measurements are consistent with the flow patterns calculated by the numerical model, in that they suggest flood tidal inflow being deflected by and incorporated into an anti-clockwise internal circulation driven by the prevailing north-westerly wind. The drogue trajectories pass several hundred metres off the wharf front with speeds of about $0.1ms^{-1}$ as they circumvent a small recirculation eddy (which is also reproduced in the model). Three of the four drogues in this group are likely to have moved beyond the influence of the subsequent ebb tidal currents. Drogue #4, entrained into the recirculation eddy adjacent to the wharf front, moved with lower speeds of about $0.04ms^{-1}$ and was located closer to the channel at the onset of ebb flow.

The other group of drogues (suspended 1-3m below the surface) were trapped in a small anti-clockwise eddy located between Bramble Point and Geak Point. This may have been due either to a vortex flow feature shed by momentum inflow or to an interplay between the tidal inflow and direct, wind-driven near-surface currents. These drogues which moved at speeds of about $0.04ms^{-1}$, showed very little penetration into Princess Royal Harbour and were not directly influenced by the main anti-clockwise, wind-driven circulation in the harbour. It appears likely that these drogues would have been swept out of the harbour on the subsequent ebb tide. This behaviour is generally consistent with the model results which show weak currents to the south-west of Geak Point under conditions of rising water and north-west winds.

No drogue measurements are available for conditions of north-west wind and falling spring tide.

4.2.2 Drogue trajectories in Princess Royal Harbour induced by tide and east wind

Figures 22, 23 and 24 show the trajectories of seven drogues tracked from about 1700 on 19 February 1986 to about 1800 on 20 February 1986. Recorded low and high water level data at Albany were 0.23m at 0530 and 0.99m at 2100 on 19 February, followed by 0.27m at 0530 and 1.16m at 2130 on 20 February. The tidal range was about 0.75m. The rising tide lasted for 16 hours and the ebbing tide lasted for eight hours. During this period the wind was fairly consistent, blowing generally from the east at about $8.5ms^{-1}$.

These conditions contrast with those of 25 August 1985 dealt with in the previous section in that the respective wind directions are opposed, although the wind speeds are similar and the tides are predominantly diurnal and of large range in each case.

Seven near-surface (1-3m and 2-4m depth) drogues were released at 1700 on 19 February, about four hours before high water. The drogue paths are shown in Figure 22. Four of these drogues (#5, #6, #8 and #9), deployed about 500m inside of the harbour entrance, moved strongly further into the harbour in a south-west direction to the left of the axis of the entrance channel. By the time of high water these drogues had penetrated, with an average speed of $0.09ms^{-1}$, to about 1800m inside the entrance. During this same time period, drogue #3 moved seaward (average speed $0.07ms^{-1}$) parallel to and within 200m of the port wharfs. The paths of drogues #9, #2 and #3 suggest the presence of a large clockwise gyre with a diameter of approximately 2000m.

The water level dropped between 2130 and 0530 and the drogue trajectories for this period are shown in Figure 23. It is of particular interest to compare the movements of drogues #2, #3 and #9 for this period. Drogue #3 had been moving seaward since 1830 (three hours before high water [HW]) and was situated off the port wharf area at 2130 (HW). It then moved rapidly

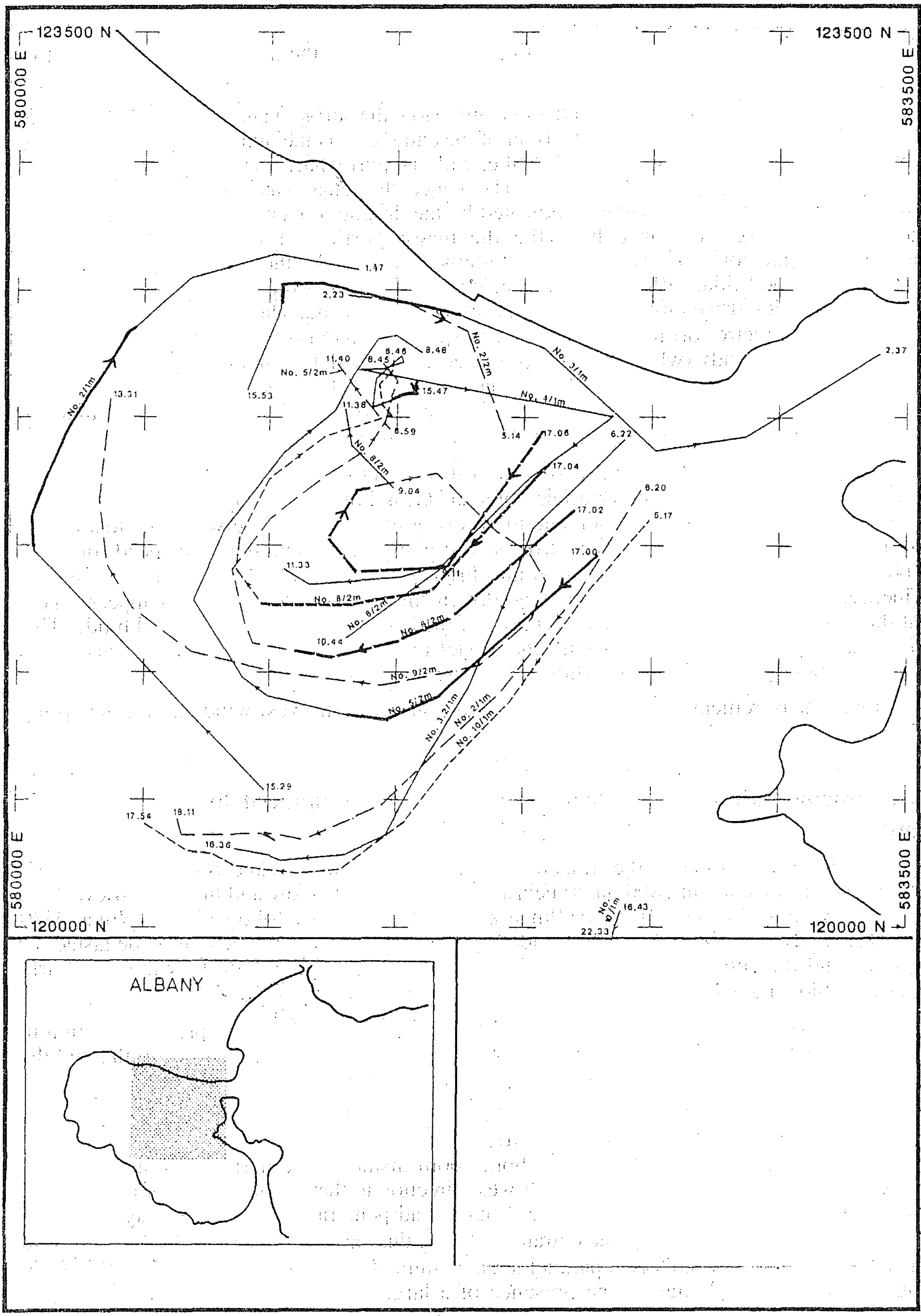

Figure 22: Drogue trajectories in Princess Royal Harbour induced by tide and east wind; 19 February 1986, 1700 to 2130

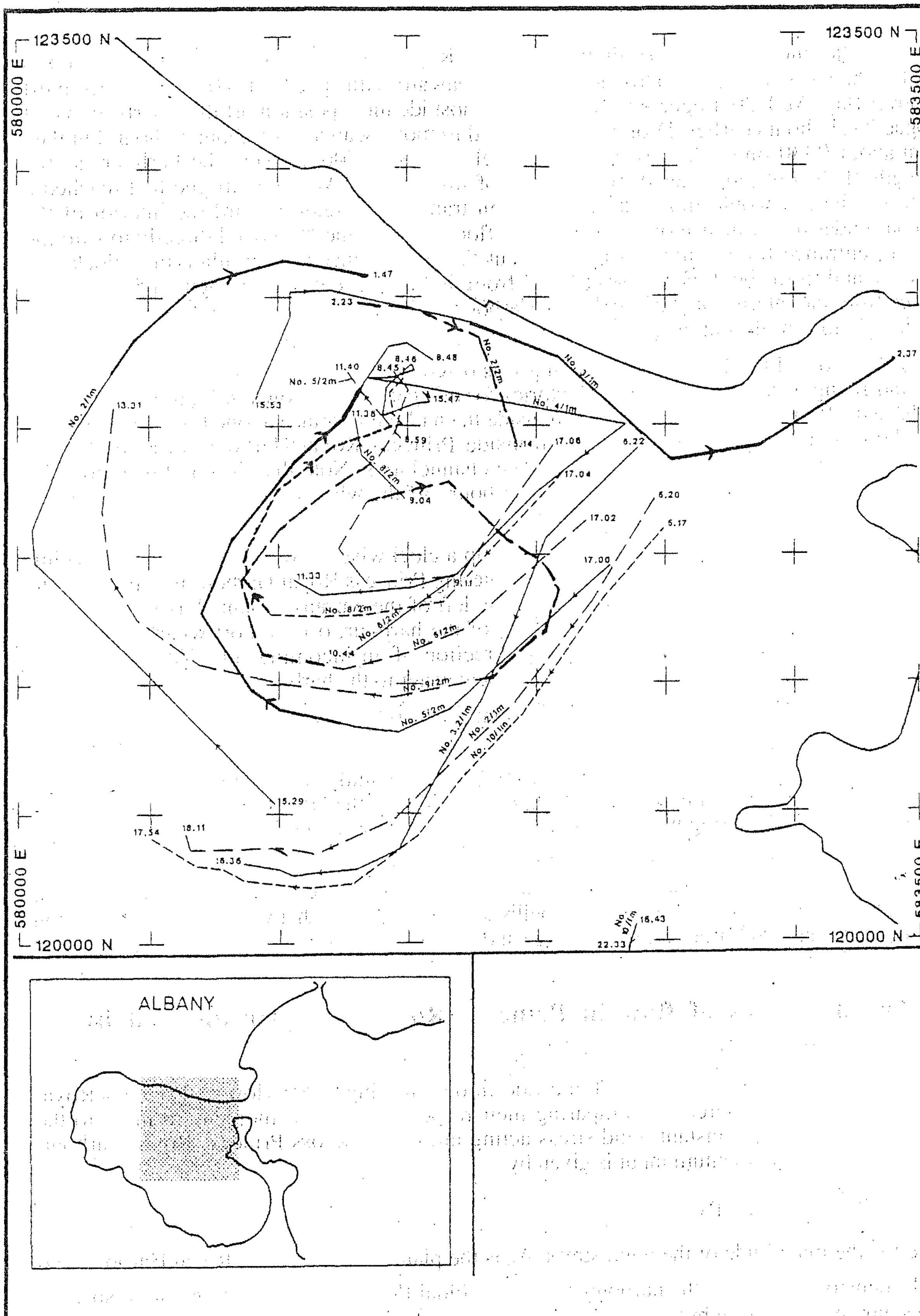

Figure 23: Drogue trajectories in Princess Royal Harbour induced by tide and east wind; 19-20 February 1986, 2130 to 0530

seaward adjacent to the northern shore of Princess Royal Harbour (with speeds up to $0.15ms^{-1}$) and left the harbour at 0130. Drogue #2 moved seaward with speeds of $0.05\text{-}0.1ms^{-1}$ from off Hanover Bay. At 0230 drogue #2 occupied an almost identical position off the wharfs to that of drogue #3 six hours earlier. Drogue #2 continued to move seaward for about an hour, but then from about 0330 onward, crossed the channel axis (still 700m inside the harbour) as the strength of the ebb tide waned. By the time of low water (LW), this drogue had reached a position where it would most likely have been transported again toward the interior of the harbour under the influence of the subsequent flood jet. Drogue #9 moved directly toward the harbour entrance for 1-2 hours after HW, but then commenced to circulate in a clockwise direction and from about 0330, moved away from the harbour entrance. Drogues #5, #6 and #8 moved from the interior of Princess Royal Harbour toward the northern side of the harbour and not directly toward the entrance channel.

From 0530 to 1811, when drogue tracking was discontinued, the tide level was rising (early and mid-rising water). The drogue trajectories for this period are shown in Figure 24. Drogues #2, #3 and #10 were released about 400m inside the harbour entrance at one hour after low tide and showed strong penetration (~2600m inside Princess Royal Harbour) in a south-west direction, deflecting to the left of the entrance channel axis. Note that during this period, the movement of drogue #6 in the north of the harbour, off the wharf area, was weak. Drogue #9 underwent an extensive clockwise circulation.

In summary, persistent winds from the east set up a clockwise wind-driven circulation within Princess Royal Harbour. On flood tide, water entering Princess Royal Harbour is entrained into this clockwise circulation and is deflected to the left of the entrance channel axis, toward the south-south-west of the harbour. To the north of the harbour, off the port wharf area, water movement is weak or even contrary to the direction of an incoming tide. The port area is therefore virtually uninfluenced by the entry of new water to the harbour.

Clockwise circulation of diameter up to 2000m is important, particularly for several hours before and after high water.

On falling tide, water leaving the harbour comes predominantly from the northern part of the harbour and wharf area. This water has been recirculated by the large clockwise gyre. In some circumstances, recirculating water may be re-jetted back into the interior of the harbour several times.

These drogue data are consistent with the understanding of water circulation in Princess Royal Harbour developed from the numerical modelling and demonstrate that wind and tide interaction is a major mechanism for net water exchange and flushing of Princess Royal Harbour.

4.3 The dynamics of flow in Princess Royal Harbour induced by wind and tide

The relative importance of the wind and tide in determining water flow in Princess Royal Harbour may be considered by comparing their respective rates of momentum input to the harbour waters. For a constant wind stress acting uniformly across Princess Royal Harbour, the rate of specific momentum input is given by:

$$M_w = \tau A_p / \rho,$$

where τ is the magnitude of the wind stress, A_p is the plan area of Princess Royal Harbour, and ρ is the density of water in the harbour. For a sinusoidal flood tide, the average rate of specific momentum input is given by:

$$M_t = 2 \pi^2 a^2 A_p^2 / (T^2 A_x),$$

where a is the tidal amplitude, T is the tidal period, and A_x is the cross-sectional area (to mean sea level) of the harbour entrance.

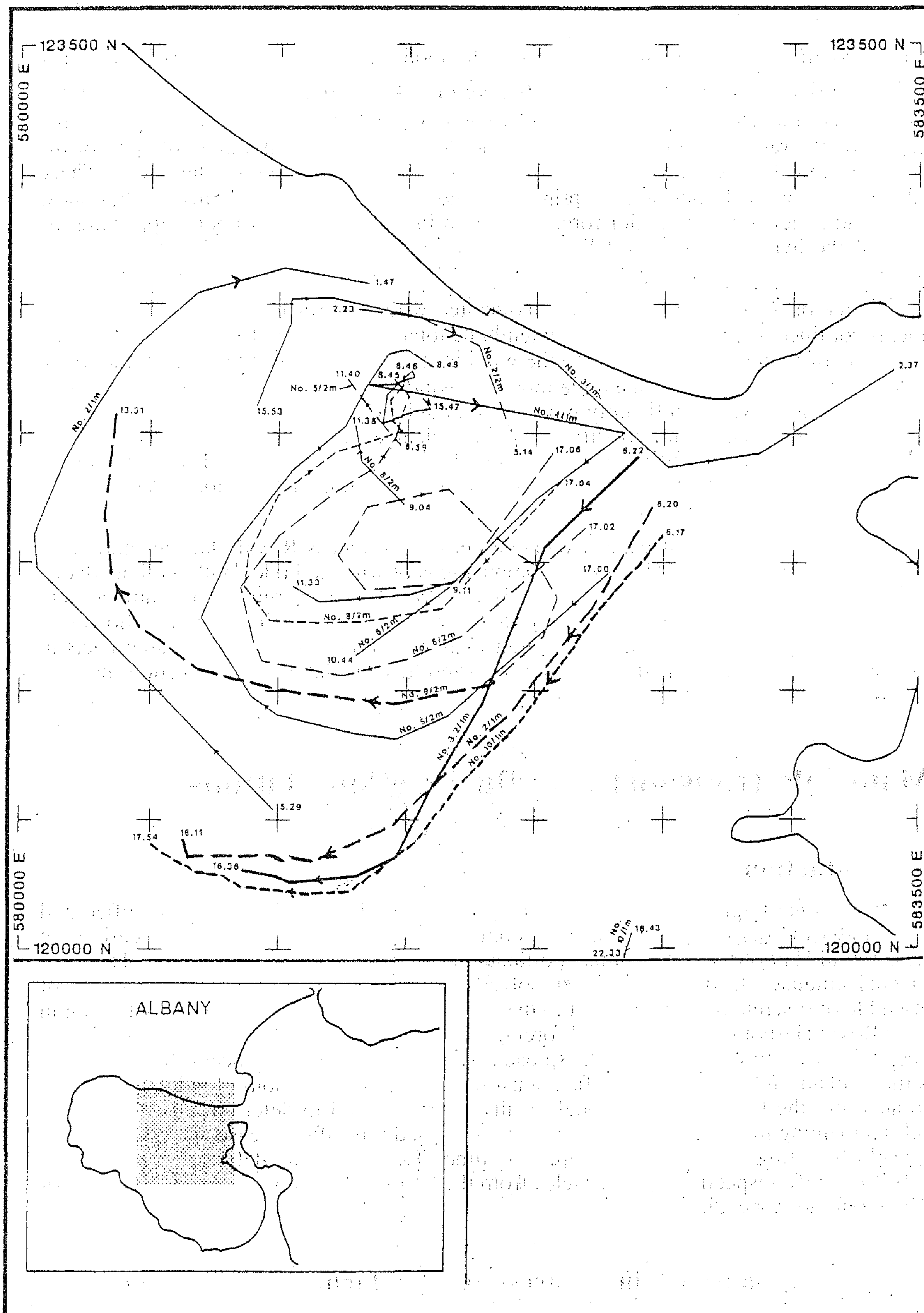

Figure 24: Drogue trajectories in Princess Royal Harbour induced by tide and east wind; 20 February 1986, 0530 to 1811

Under the conditions of wind and tide used in the model run, $\tau = 0.1$Pa, a = 0.5m and T = 86400s. For Princess Royal Harbour, $\rho \sim 1023$ kg m^{-3}, $A_p = 2.9 \times 10^7 m^2$, and $A_x = 3500m^2$. For these values the rate of momentum input by wind ($M_w = 2800m^4s^{-2}$) dominates by an order of magnitude the rate of momentum input by tide ($M_t = 150m^4s^{-2}$) although only part of the momentum input by the wind stress is transferred to the mean flow of the water. These calculations are for conditions of near spring tides and moderate winds (~ $7.5ms^{-1}$). They show that the wind is generally the major forcing agent in Princess Royal Harbour, supporting the findings of the hydrodynamic modelling and field data analysis presented in the previous sections.

In the absence of wind, strong water flow associated with the Princess Royal Harbour flood tidal jet is confined to an area of about one tenth the total harbour area. Even over this limited area, the rate of momentum input due to the wind is still of the same order as that due to the tide. Hence, it is to be expected that quite moderate winds of reasonable duration (e.g. $7.5ms^{-1}$ winds for six hours) will significantly modify the circulation pattern due to tidal momentum injection alone. This will in turn modify the water exchange and flushing regime. Both model and drogue trajectory data confirm that the action of wind stress on Princess Royal Harbour is able to strongly modify the flow patterns which result from tidal action alone. Wind-driven circulation tends to dominate in the interior.

The model results shows that water exchange between Princess Royal Harbour and King George Sound can be promoted by certain combinations of wind and tide. With our knowledge of wind-driven circulation patterns (Mills and Brady, 1985) it can be argued that south-east and south-west winds will also promote efficient water exchange. North-east winds however, favour a movement of water towards the entrance channel along the axis. This pattern acts in opposition to the bias in the tidal jet circulation. Therefore this latter wind direction may not favour efficient exchange.

5 Materials transport and flushing simulations

5.1 Introduction

A two-dimensional Lagrangian particle-tracking technique (Hunter, 1987) was modified and used to model the dispersion of dissolved contaminant discharged at several locations in Princess Royal Harbour and to estimate pollutant flushing times for Princess Royal Harbour. This model simulates the dispersion of a dissolved contaminant cloud by tracking the spread of an ensemble of discrete particles subject to the advection and diffusion processes obtaining in Princess Royal Harbour under specified forcing conditions of wind and tide. The Lagrangian transport model was used to simulate the spread and eventual exit from Princess Royal Harbour of particle streams released from specific points (representing the locations of industrial outfalls and drains into the harbour). The model results were analysed to determine the number of particles remaining in the harbour as a function of elapsed time after release and on this basis, harbour flushing times were deduced. Flushing times T_{90} and T_{64} are defined as the times to lose 90% and 64% respectively, of particles from the harbour by export. For further details of the model refer to Appendix 3.

5.2 Materials transport in Princess Royal Harbour under tidally-induced flow

The Lagrangian transport model was first run with the current velocity results from the purely tidal hydrodynamic simulation. As indicated in Section 3.1, the current velocity field for Princess Royal Harbour under purely tidal conditions is highly variable in space with significant currents occurring in the flood tidal jet and the recirculation and ebb flow features near the harbour entrance, but very weak currents persisting over much of the harbour. Hence, as might be expected, the flushing times as determined by the Lagrangian transport model are highly dependent on the location of particle release, with T_{90} ranging from the order of 100 days to several days. Since extended periods of calm rarely occur in Albany, these results will not be detailed further.

5.3 Materials transport in Princess Royal Harbour under flow driven by combined wind and tide

The transport model was run to examine the fate of particles released to the harbour under hydrodynamic conditions generated by combined wind and tide forcing. The hydrodynamic model results for a diurnal spring tide (range 1m) and a steady 7.5ms^{-1} north-west wind (discussed in Section 4.1) were used to provide current velocity data to the transport model. The effluent source locations used in the simulations approximate actual industrial outfall and drainage locations and are shown in Figure 1.

The results of the transport model simulation suggests that much of the dissolved/suspended materials released as effluent from the north and north-west shore tend to be transported in an anti-clockwise direction, moving about the south-west side of the harbour, prior to circulating back close to the entrance where there is some chance of tidal flushing. Figure 25 illustrates the simulated trajectory of the centre of mass of particles released from source 2 under the above hydrodynamic conditions.

The total number of particles remaining in the model domain was derived as a function of the elapsed time since effluent release. Figure 26 provides an example of the particle flushing simulation from source 2. Table 4 shows the flushing time estimates for dissolved pollutants released at several locations in the harbour obtained from the model results.

Table 4: Model-derived estimates of effluent flushing time for Princess Royal Harbour from several source locations. (diurnal tide range: 1m; wind: north-west at 7.5ms^{-1})

Effluent Source Location	T_{90} (days)	T_{64} (days)
1	8.25	3.75
2	9.75	5.00
3	10.75	5.75
4	10.25	5.75

* Effluent source locations are indicated in Figure 1.

Table 4 indicates that under the specified tide and wind conditions the flushing times for effluent released to the harbour vary little with the location of the release point. The smallness of this range of flushing times is indicative of the horizontal mixing efficiency of the wind-driven circulation gyres. The results suggest that for these conditions, more typical of winter, the siting of effluent pipelines along much of the northern shore, relatively near the harbour entrance, is of little advantage in terms of dissolved pollutant flushing times. That is, recirculation of effluent about the harbour dominates immediate tidal flushing and there is a strong tendency for pollutant from almost any source location to be mixed throughout the harbour, and to be available for biological uptake prior to export. A different relationship between flushing time and source location is likely to apply in summer.

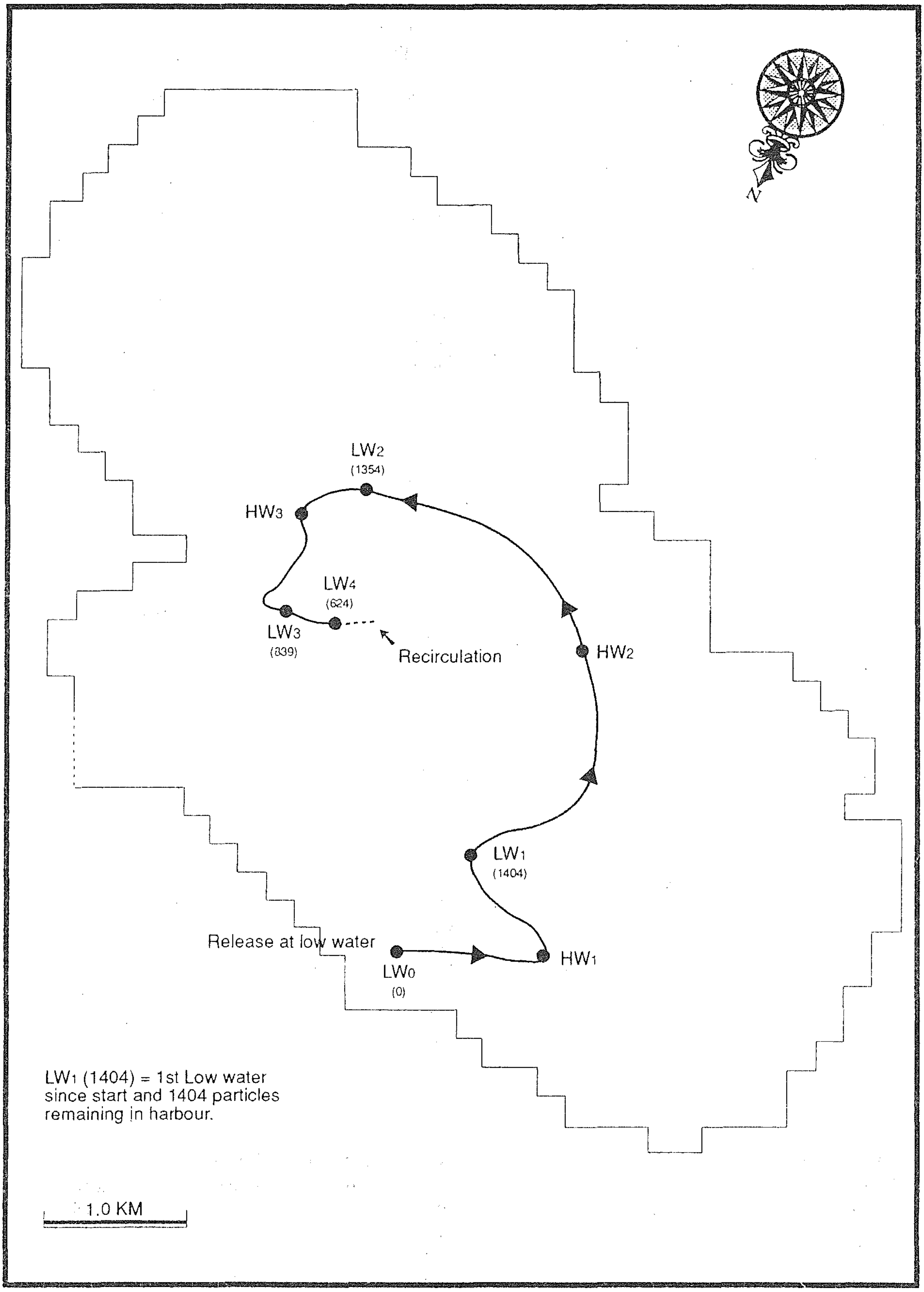

Figure 25: Modelled trajectory of the centre of mass of effluent released in Princess Royal Harbour (from source 2) for a diurnal spring tide of range 1m and north-west wind of 7.5ms^{-1}

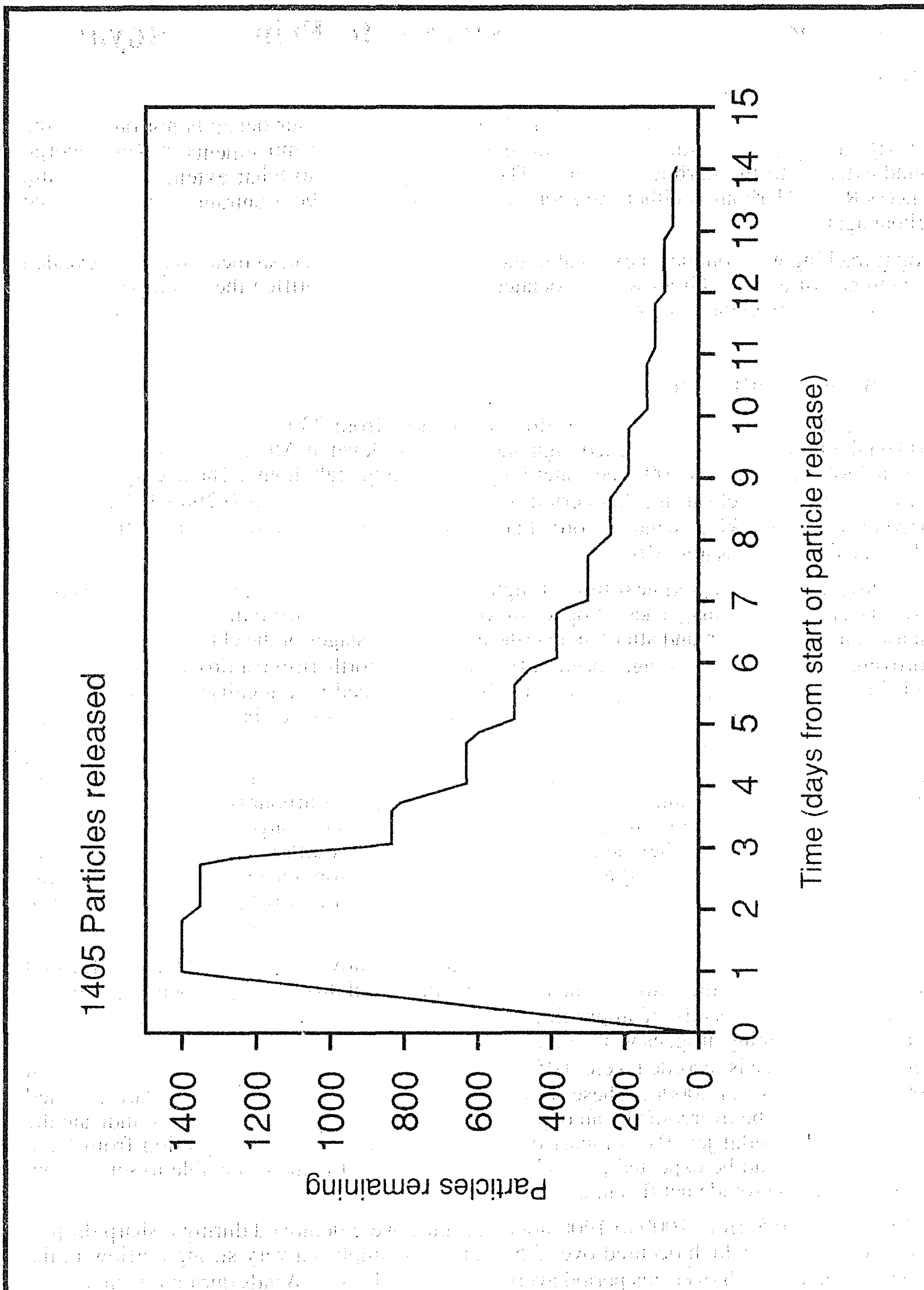

Figure 26: The number of model effluent particles remaining in Princess Royal Harbour as a function of time after initial release. 1405 particles emanated from source 2 during a 24-hour period from low water to low water. Forcing conditions were a diurnal tide of range 1m, and north-west wind of 7.5ms^{-1}

6. Hydrodynamic results external to Princess Royal Harbour

The flushing of water and materials from Princess Royal Harbour depends not only on the hydrodynamic regimes within the harbour, but also on the water movements in King George Sound external to the harbour entrance. The latter determine to what extent water exiting Princess Royal Harbour is either transported away from the harbour entrance or re-enters the harbour again.

Drogue tracking was conducted external to the harbour entrance. These measurements revealed the presence of a tidal ebb jet with associated vortices, and identified the influence of water circulation in King George Sound.

6.1 The ebb tidal jet

Figures 27-29 show the trajectories of drogues tracked from 2300 on 23 February 1986 to 0900 on the following day. Recorded high and low water level at Albany for this period were 1.4m at 2300 and 0.5m at 0700. The water level fell 0.9m in eight hours. The average speed of outflow in the channel during this period was therefore calculated as $0.26 ms^{-1}$. During the period of drogue tracking, winds recorded at Albany airport were initially 4 ms^{-1} from 270°, and weakening to calms after 0100.

Seven drogues were released near time of high water (~2300) immediately outside and spread across the entrance channel. These drogues moved (Figure 27) out from the entrance channel in a quasi-radial distribution and after 5 hours (the early to mid stages of the ebb tide) had travelled approximately 1km at an average speed of $0.08 ms^{-1}$. The northern-most drogue, suspended at 5m below the water surface, appears to have been influenced by a localised vortex as (from about 0140) it was circulated in an anti-clockwise direction and moved back toward the harbour entrance.

Figure 28 illustrates the flow field during mid to late ebb flow. Five drogues were relocated, four across the entrance channel, just outside of Princess Royal Harbour (in similar locations to the initial deployment). Between 0400 and 0800 these drogues no longer displayed a tendency to fan out radially. Rather, they demonstrated more vigorous outflow within a band of width equal to the entrance channel and to distances of 1900m out from the channel. Typical drogue speeds were $0.15\text{-}0.20 ms^{-1}$ up to 500m outside the channel and $0.11\text{-}0.16 ms^{-1}$ from 500-1500m out from the channel.

From 0700 to 0900 the water level rose. Figure 29 shows that two drogues, located immediately outside of the entrance channel (along the initial drogue deployment line) moved into the channel at speeds of approximately $0.20 ms^{-1}$. However, further away from the entrance, the remaining drogues were still moving away from the channel at this time. Outward-directed drogue speeds recorded were $0.05 ms^{-1}$ at 500m distance from the channel, $0.11 ms^{-1}$ at 1200m and $0.07 ms^{-1}$ at 2000m. These results indicate that it takes time for outward-directed momentum flux to be overcome by an opposing pressure gradient force. They also indicate the extent of the ebb tidal jet. By comparison, the maximum radius of abstraction from King George Sound would be expected to be about 1000m. The jet is therefore able to set up flow asymmetry and to provide net flushing.

On 15 August 1985, from 1000 to 1900 hours, drogues were deployed during a sharp drop in water level (0.65m) which occured over 3.5 hours. This implies a very strong outflow in the entrance channel which over this period averaged about $0.42 ms^{-1}$. Winds during this time were light and variable. Nine drogues were released across the width of the channel and just outside. Figure 30 shows that all of the drogues released across this section were drawn into a vortex pair, soon after the beginning of the ebb flow, in a manner similar to that described by Wilkinson (1978) with an anti-clockwise vortex to the north (of diameter ~ 500m) and a clockwise vortex to the south (of diameter ~ 1000m). One drogue, after spinning tightly once in the northern vortex, found itself (at about 1700) located again in front of the channel and about

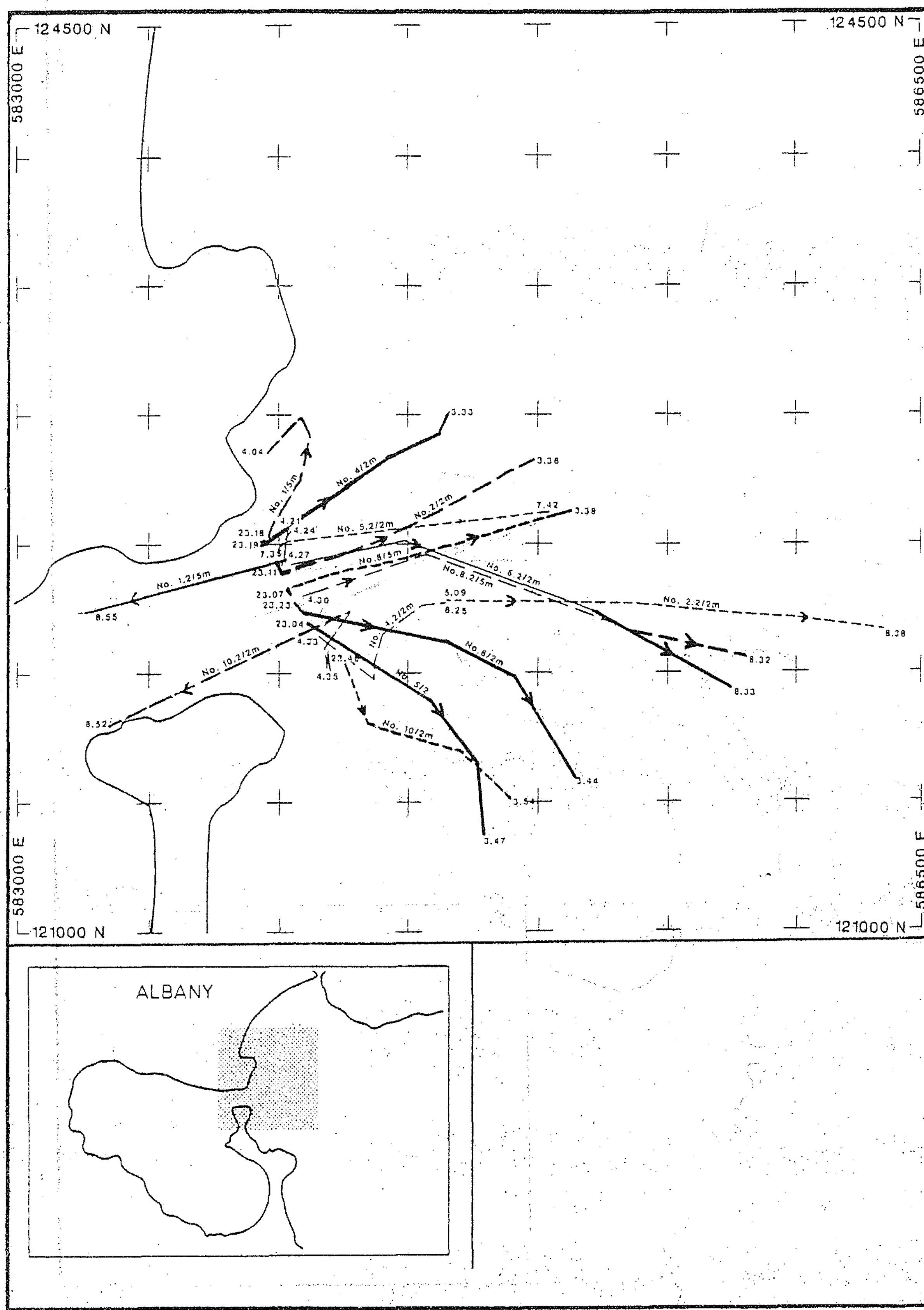

Figure 27: Drogue trajectories in King George Sound induced by ebb tide and calms; 23-24 February 1986, 2300 to 0400

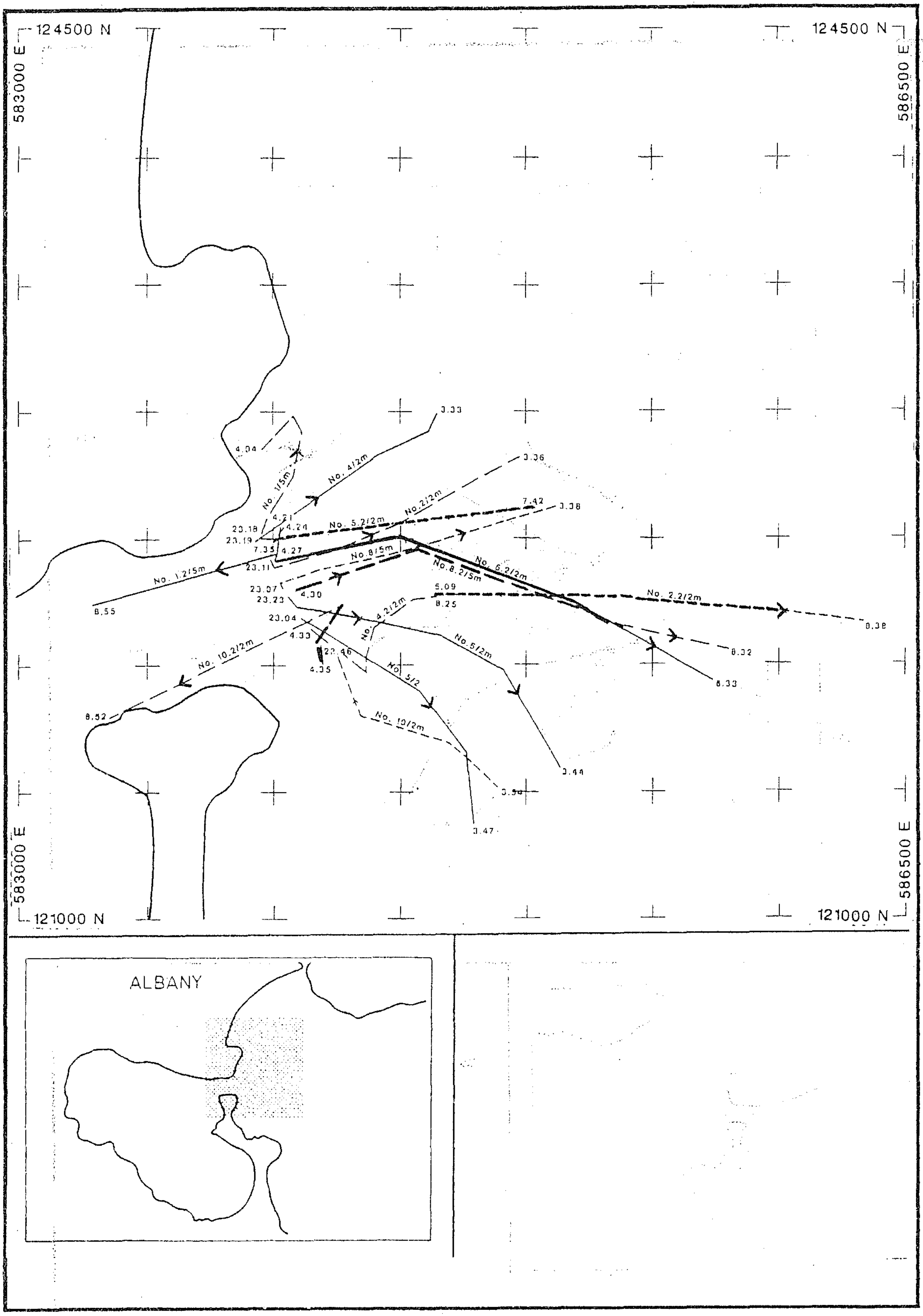

Figure 28: Drogue trajectories in King George Sound induced by ebb tide and calms; 24 February 1986, 0400 to 0700

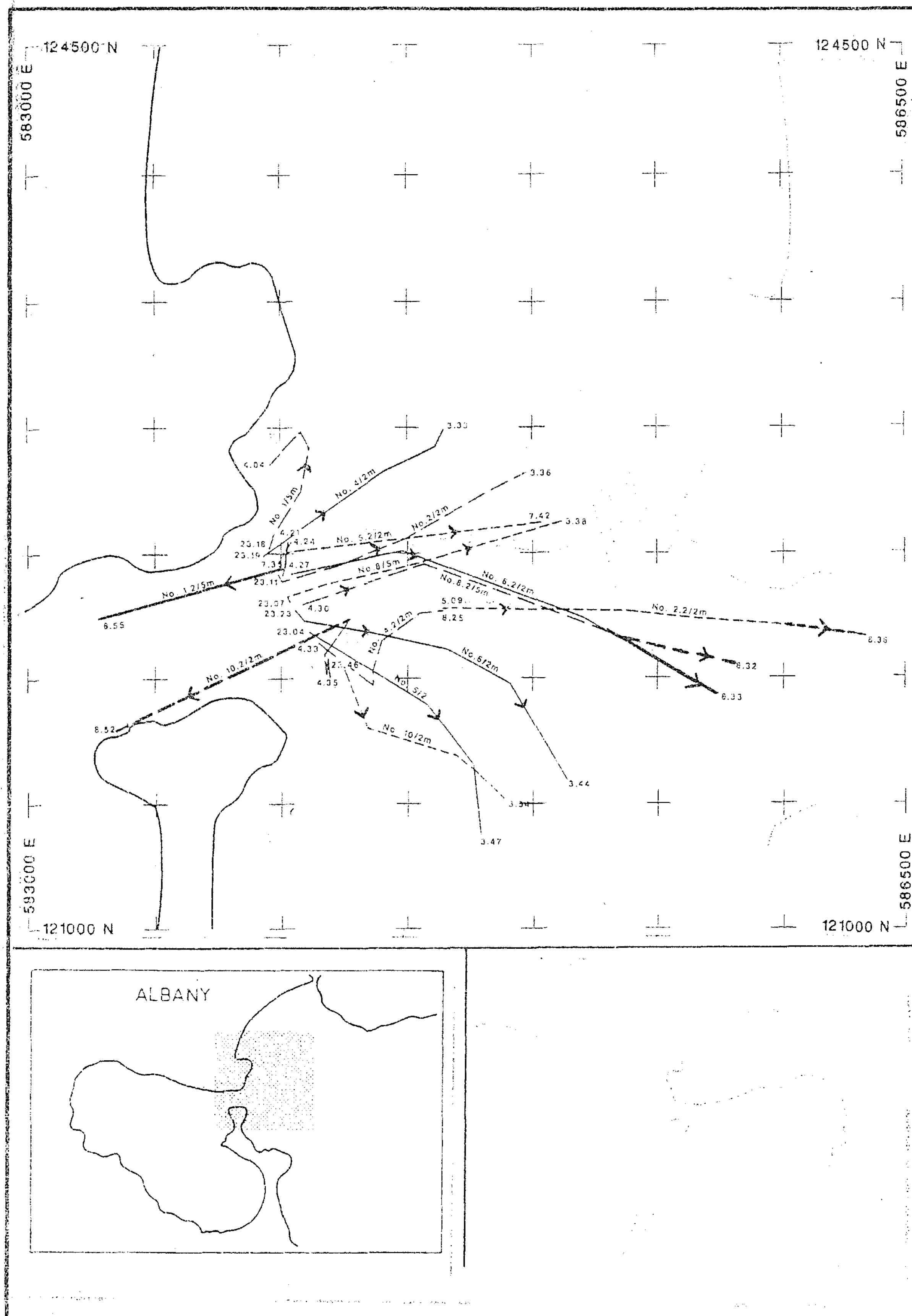

Figure 29: Drogue trajectories in King George Sound induced by ebb tide and calms; 24 February 1986, 0700 to 0900

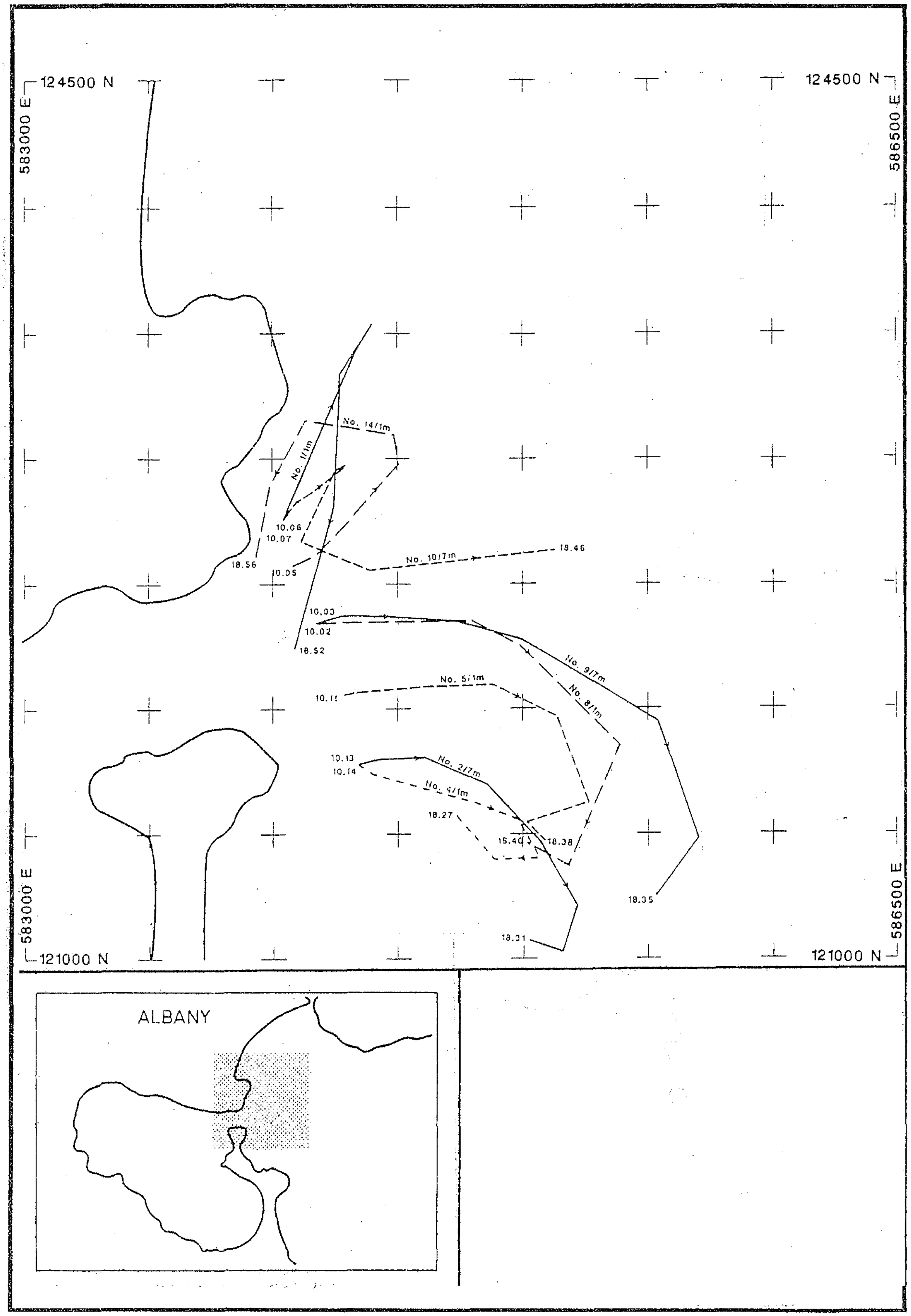

Figure 30: Drogue trajectories in KIng George Sound induced by ebb tide and calms; 15 August 1986, 1000 to 1900

300m outside the initial section of release. From then on, this drogue showed movement parallel to the axis of the channel and may represent the onset of the tidal jet, following the initial vortex pair curl-up phase.

Particular note should be taken here of the potential for water entrained into the northern vortex to remain close to the Princess Royal Harbour entrance channel. It is highly likely that some of this water would re-enter the harbour, hence the possibility of re-entry of pollutant initially discharged to and flushed from the harbour. This northern vortex is also situated adjacent to the King Point municipal wastewater ocean outfall and there is potential for this nutrient-rich effluent to be drawn into Princess Royal Harbour under these conditions.

6.2 The influence of King George Sound circulation near the Princess Royal Harbour entrance

The characteristics of the tidal ebb outflow from Princess Royal Harbour to King George Sound were identified in the previous section, under conditions of weak wind. In this section several drogue tracking experiments will be documented which illustrate the influence of wind forcing on the King George Sound waters and on the pathways and net exchange of water emanating from Princess Royal Harbour.

6.2.1 South-south-east wind and ebb tide

Figure 31 shows the trajectories of drogues tracked from 0930 to 1754 on 13 August, 1985. Predicted high water for Albany was 1.17m at 0900 and low water was 0.34m at 1730, indicating a fall of 0.83m in 8.5hr. The average speed of outflow in the channel was therefore calculated as $0.22ms^{-1}$. During this period winds were south-south-east (140°-180°) at speeds of 3 to $6ms^{-1}$.

Four near-surface (1-3m) and four deep (7-9m) drogues were released near the time of high water. In general, the drogues showed clockwise rotation to the south of the entrance channel, and counter-clockwise rotation to the north. Two near-surface drogues (#6 and #10) underwent complete and opposite circuits and returned toward the central axis line of the channel from either side. Near surface drogues (#1 and #4) deployed in front of and to the north of the entrance channel were advected downwind, 1400m to the north (into Middleton Bay). Drogue #1 was deployed in close proximity to to the King Point wastewater outfall and suggests that under these conditions, effluent from the outfall could be advected into Middleton Bay within seven hours.

6.2.2 North-west wind and early flood tide

Drogue tracking during the evening of 27 August and the early morning of 28 August 1985 illustrated flow patterns in King George Sound, just outside of Princess Royal Harbour, under conditions of moderate north-west winds and the early flood tide (see Figure 32). Predicted low water for Albany was 0.29m at 1800 on the 27th and the subsequent predicted high water was 1.22m at 1000 on the 28th. This represents a rise of 0.93m in 16 hours, corresponding to an average channel inflow current of $0.13ms^{-1}$. *In situ* winds were $3\text{-}8ms^{-1}$ from the north-west.

Nine drogues were deployed in two lines across the entrance channel at about 1730 on 27 August, 1985 (just prior to low water) and tracked until 0300 during the first half of the flooding tide. Figure 32 shows that the deeper (7-9m) drogues #1 and #5 responded within 1.5 hours to the onset of the flood tide into Princess Royal Harbour and from that time recirculated back towards the entrance channel. During that same initial period, five surface (1-3m) drogues moved initially at a greater rate (~ $0.11ms^{-1}$) away from the harbour entrance, and continued moving east-north-east into King George Sound for about 900m before being deflected suddenly to south at about 2100. The absence of extensive eddying or vortex flow features is

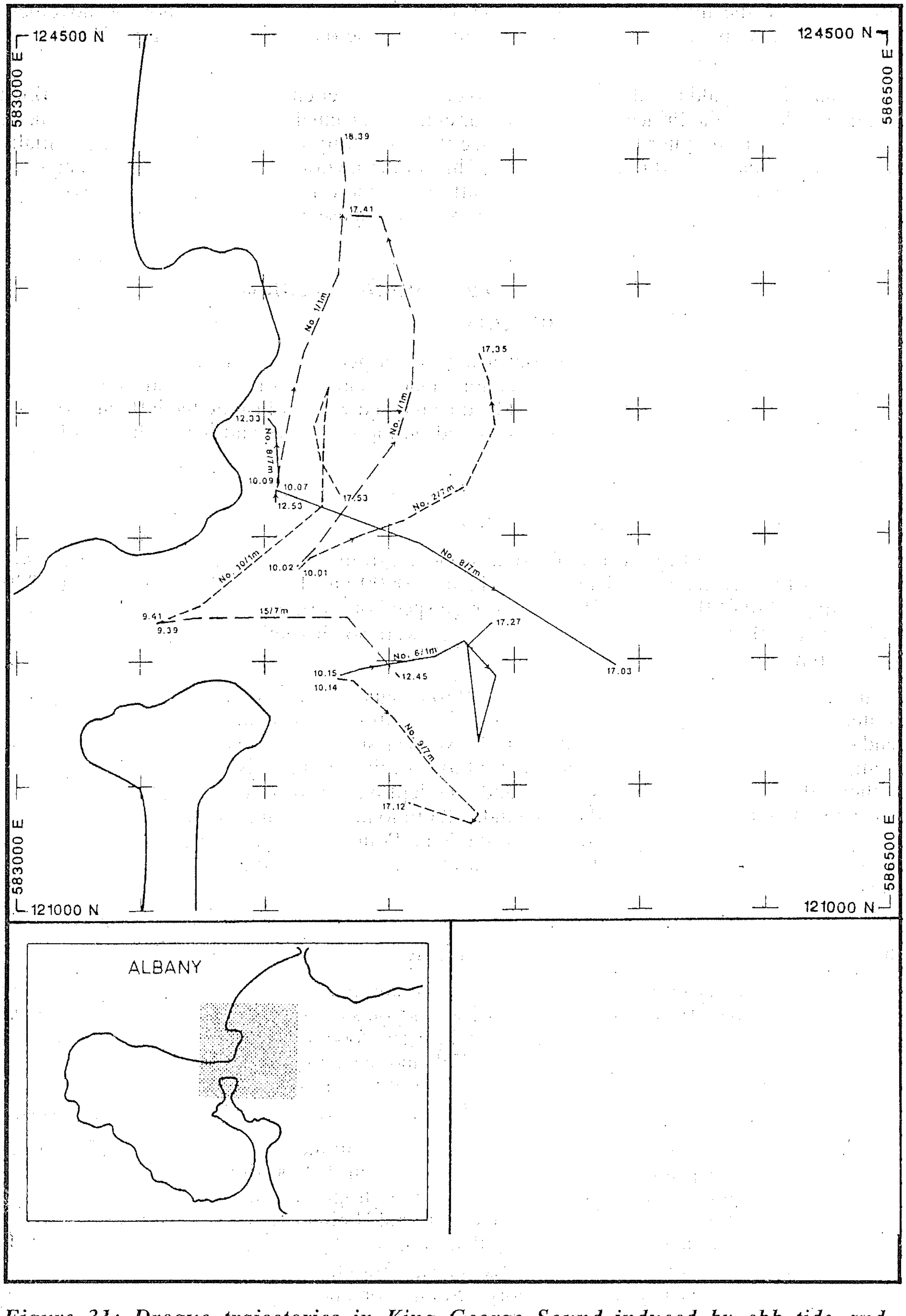

Figure 31: Drogue trajectories in King George Sound induced by ebb tide and south-south-east wind; 15 August 1985, 0930 to 1754.

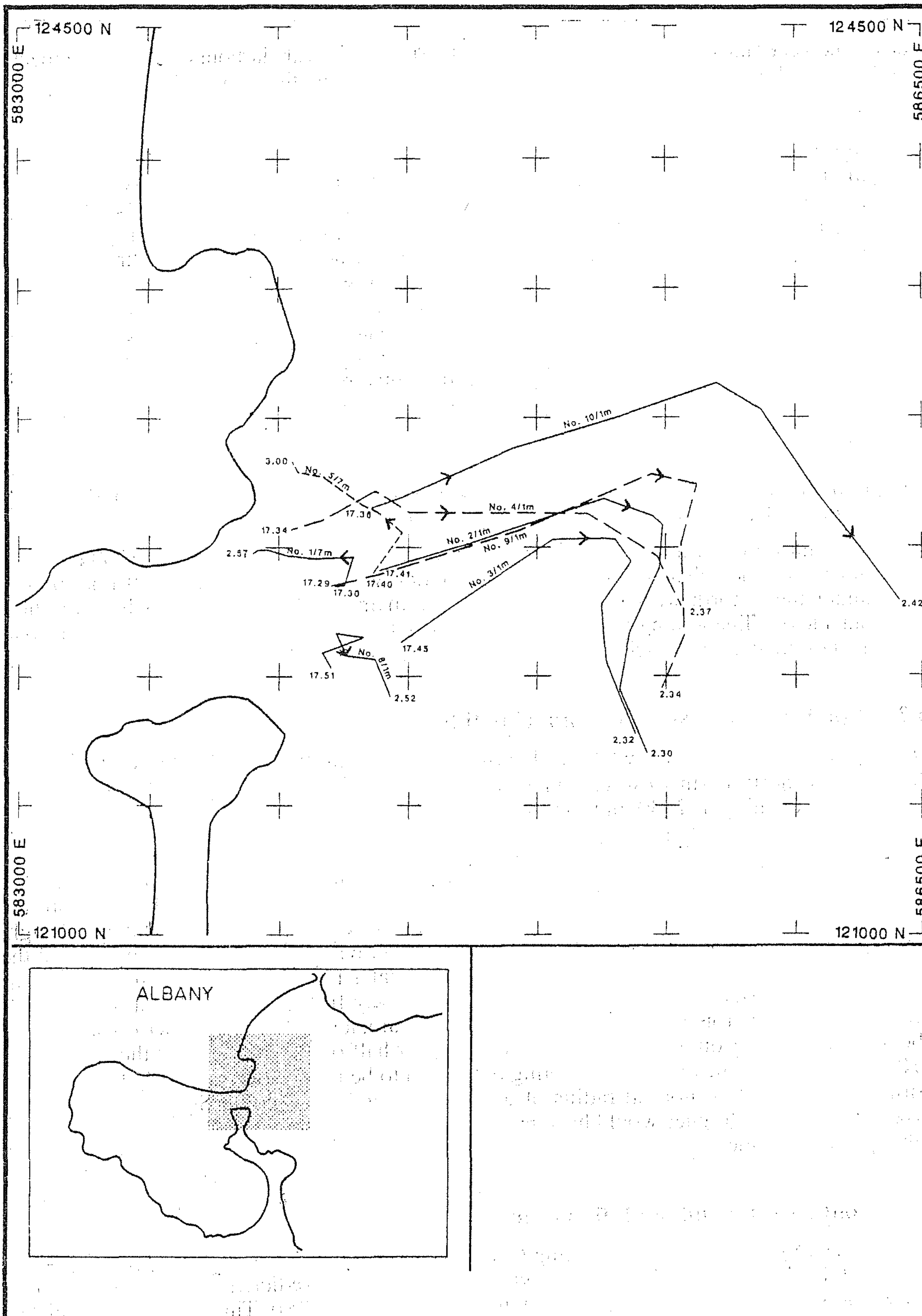

Figure 32: Drogue trajectories in King George Sound for early flood tide and north-west winds; 27-28 August 1985, 1730 to 0300.

noted. The generation of such features external to Princess Royal Harbour is not to be expected toward the end of the ebb (decelerating channel flow) or during the flood (Wilkinson, 1978).

These surface drogues may have been affected by three factors:

- initially they may have moved primarily under the influence of residual outflow momentum, generated by the previous ebb tide (which involved a water level fall of 0.9m in 8.5 hours, implying an average entrance channel current of $0.24ms^{-1}$). This explanation is consistent with the observation that these near-surface drogues moved largely parallel to the entrance channel axis and perpendicular to the wind direction and to the main trend of the coastline. Shortly after low water there is a horizontal pressure gradient which sets up a force toward the entrance channel and therefore causes water to accelerate in this direction. At low water, the water speed in the channel is zero and outside the channel, jet flow continues under momentum generated during the previous ebb tide. Hence the acceleration will initiate inward flow with short delay (after low water) near the entrance channel, but acceleration will take longer to annul the outward momentum of water further away from the entrance channel.
- given the north-west wind direction, and the presence of a steep, cliffed coastline situated immediately upwind of the points of drogue release, the water outside and near the entrance channel may have been significantly sheltered from the action of wind stress.
- the southward deviation did not occur until the drogues were located about 1500m outside of the entrance channel, and then the deviation was reasonably abrupt. It may be that under these north-west wind conditions, the main wind-driven flow is held offshore outside of a line joining Wooding Point to Mistaken Island, which also corresponds to an area of greater wind fetch.

6.2.3 North-north-west wind and ebb tide

Drogue tracking was conducted on 23 February 1986 during the period 0000 to 0920. Wind direction was north-north-west with wind speeds up to $11ms^{-1}$. High water of 1.38m occurred the previous evening at 2330 and low water of 0.44m occured at 0630. The water level fell 0.94m in 7.5 hours, implying an outward flowing current in the entrance channel of $0.28ms^{-1}$.

Figure 33 illustrates the drogue trajectories for this period. Most of the drogues were released to the north of the alignment of the channel axis at distances from 400 to 1000m out from the channel opening. The near-surface drogues released closest to the channel underwent tight (250m diameter) near-field (within 1km) counter-clockwise rotations during the first half of the ebb tide (0130-0400) and subsequently moved to greater than 2km away from the harbour entrance. Near-surface drogues released about 1km away from the harbour entrance moved north-north-west before undergoing larger (500m diameter) counter-clockwise rotations at about 1500m away from the entrance during the latter half of the ebb tide and the early flood (0400-0900). All of the drogues, excepting one, seem to be transported generally to the north-north-east, beyond the normal radius of abstraction for King George Sound, and it is not expected that these drogues would have re-circulated back into Princess Royal Harbour on the subsequent flood tide.

6.2.4 South-west wind and flood tide

Drogue tracking was conducted in King George Sound on 23 February, 1986, from 1040 to 2116, and the drogue trajectories are shown in Figure 34. The predicted tide at Albany for this day was low water (0.33m at 0600) and high water (1.24m at 2300). This indicated a tidal rise of 0.91m in 17 hours, implying an average current speed through the channel of $0.12ms^{-1}$. The observed winds during this period were south-west to west with speeds of 5 to $8ms^{-1}$. Near-surface drogues (1-3m) were trending north-east at about $0.1ms^{-1}$ across Middleton Bay. Deeper drogues (4-6m) were moving in a similar direction, but at speeds of $0.06ms^{-1}$. It appears that, well into the flood tide (4-6 hours after low water), drogues at distances of 1km or

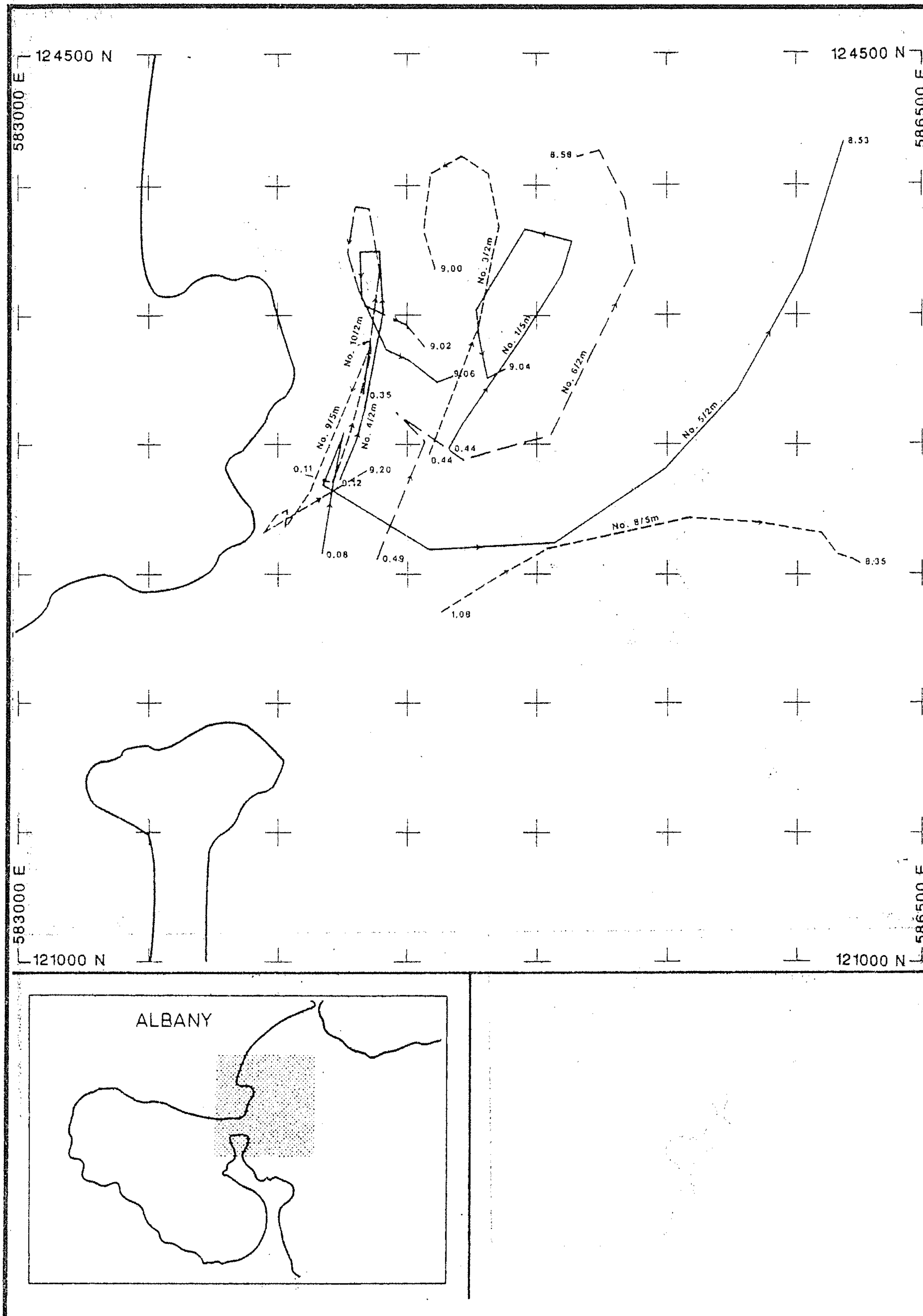

Figure 33: Drogue trajectories in King George Sound for ebb tide and north-west winds; 23 February 1986, 0000 to 0920.

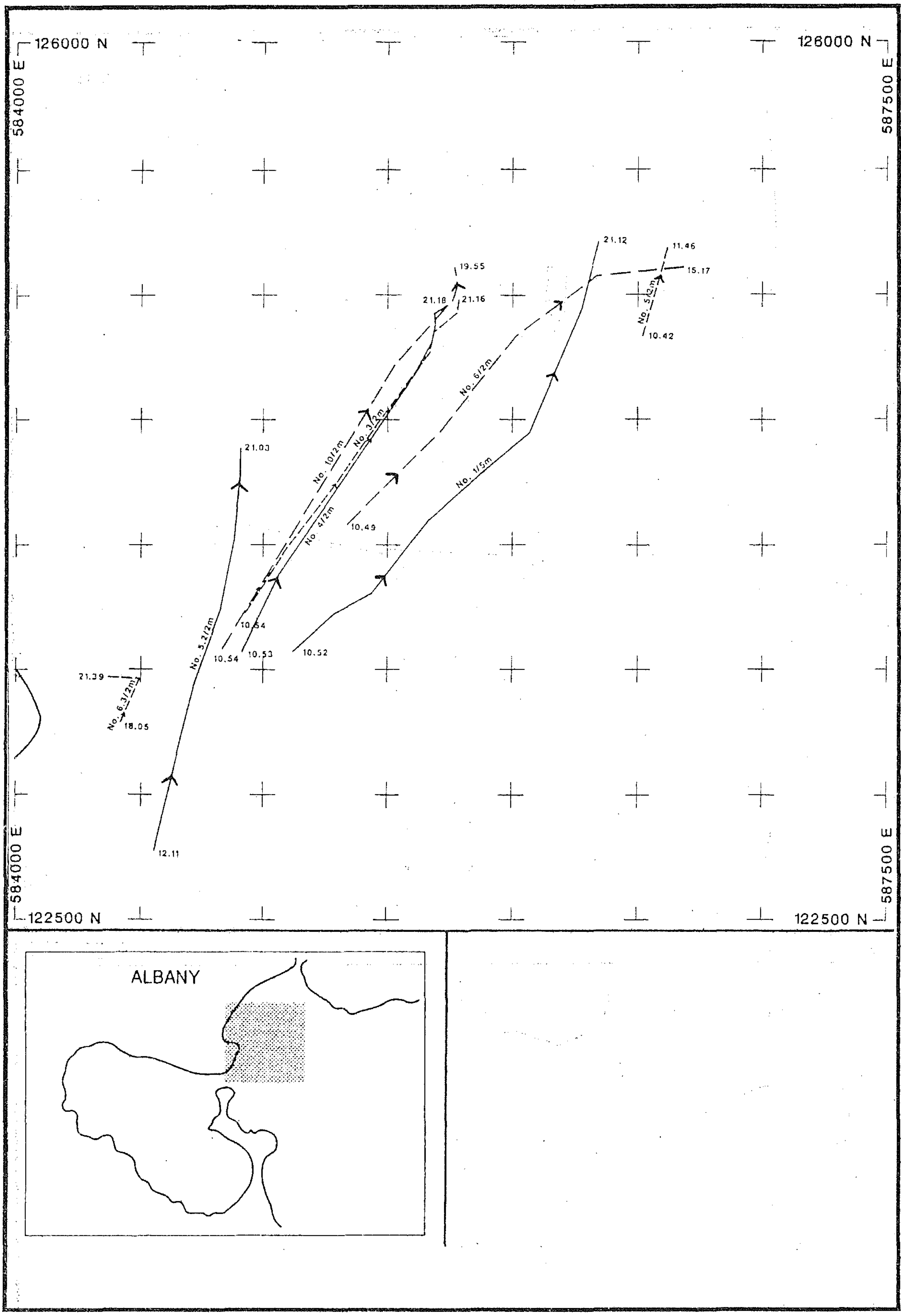

Figure 34: Drogue trajectories in King George Sound foflood tide and north-north-west winds; 23 February 1986, 1040 to 2116

greater from the mouth of Princess Royal Harbour were not drawn back toward the harbour under these conditions but were being influenced by the wind-driven circulation of King George Sound. Hence, there is clearly potential for the transport of effluent from sources within the harbour and from the King Point wastewater outfall into the vicinity of Middleton Beach and across Middleton Bay.

7. General discussion

7.1 Fate of effluents

The movement of effluent discharged to Princess Royal Harbour is determined by the effluent characteristics (e.g. the effluent material may be buoyant, dissolved or settling particulate) and its mixing and transport by the water movements.

Buoyant pollutant materials (e.g. fat, oil, grease) remain at or near the water surface and are affected by water movement at that level. Such materials generally move downwind at about 3% of the wind speed (e.g. Bowden, 1983) unless caught in strong tidal currents, e.g. in the entrance channel on peak flood or ebb current. Dissolved or fine suspended pollutants are more uniformly distributed throughout the water depth, reflecting the ability of the wind to vertically mix the weakly stratified harbour waters. The movement of these dissolved and suspended materials is predominantly influenced by the tidal currents and the wind-driven horizontal gyres.

For example, in deep water, off the wharf area under strong north-west winds, surface-residing matter is driven in a south-east direction (down wind), and much of the dissolved and suspended matter is transported at greater depth to the north-west as part of the return flow in an anti-clockwise gyre.

Much of the dissolved/suspended effluent discharged to Princess Royal Harbour emanates from industrial outfalls on the north shore or an agricultural drain to the north-west of the harbour. For unstratified conditions, vertical mixing of passive contaminant is achieved within a downstream distance of the order about 10-100 times the flow depth. Assuming this to be the case for the deeper, northern portions of Princess Royal Harbour, a point discharge will become vertically well mixed within a distance of approximately 1000m. In winter, under north-west to west winds, these materials tend to be transported about the harbour in an anti-clockwise direction, moving about the south-west side of the harbour, prior to circulating back toward the harbour entrance. In summer, under east to south-east winds, these materials initially move clockwise along the northern shore, but on flood tide, can be recirculated far into the south-west interior of the harbour.

7.2 Flushing times for Princess Royal Harbour

The flushing time for Princess Royal Harbour can be considered in terms of a mass of dissolved material introduced into Princess Royal Harbour at a given time and location, and defined as the time required for a specified percentage of this material to be lost from the harbour through flushing processes.

The "particle tracking" model simulations were run for conditions of steady wind and a repeating tidal range, yielding 90% flushing times of about 10 days. Flushing times were relatively insensitive to the point of effluent release for these wind and tide conditions. In reality:

(a) winds are variable in direction and speed and the resultant water circulation in Princess Royal Harbour less coherent than for constant wind;
(b) tidal range varies, and is usually less than 1m; and
(c) on each flood tide there is some re-entry of water which left the harbour on the ebb tide.

Because of these factors, a 90% flushing time of 10-20 days is estimated.

7.3 Mixing, circulation, nutrient exposure to plants and algae mobility

The waters of Princess Royal Harbour are frequently well mixed vertically by the action of wind (Section 1.5). This suggests that dissolved and suspended nutrients introduced to the water column are also well mixed vertically and that these nutrients frequently contact the benthic plant communities of Princess Royal Harbour. This is consistent with the large biomass of benthic algae measured in Princess Royal Harbour. Hillman *et al* (1990b) reported that macroalgae now accounted for over 80% of plant biomass in the formerly seagrass dominated Princess Royal Harbour. Hillman *et al* (1990a) also reported low nutrient and chlorophyll concentrations in Princess Royal Harbour waters and high water clarity similar to levels found over healthy seagrass meadows in King George Sound. The combination of large algal biomass in the harbour, coupled with the low levels of nutrients in the clear harbour waters further suggests that the hydrodynamic flushing times of Princess Royal Harbour are considerably longer than the times required for nutrient uptake by the benthic algae.

7.4 Bottom wave orbital velocities

Following procedures outlined in U.S. Army Coastal Engineering Research Centre (1975), the strengths of bottom wave orbital speeds were calculated to assess the importance of these motions to re-suspension of sediments and mobilisation of benthic algae. The results are shown in Table 5.

Table 5: Predicted bottom wave orbital velocities for selected water depths in Princess Royal Harbour and selected wind conditions, with maximum wind fetch

Wind speed (ms^{-1})	Wind direction (°N)	Water depth (m)	Bottom wave orbital speed (ms^{-1})
7	135	2.8	0.04
15	135	2.8	0.26
30	135	2.8	0.62
7	135	4.0	0.01
15	135	4.0	0.13
30	135	4.0	0.44

For typical moderate winds ($7.5ms^{-1}$) and maximum wind fetch, the wave orbital velocity at the bottom (BOV) in water depths of 2.8m are small ($0.04ms^{-1}$) and unlikely to be able to mobilise benthic algae. However, for gale force winds ($20ms^{-1}$) the BOV increases dramatically ($0.38ms^{-1}$) and creates conditions probably energetic enough to move benthic algae. For the same range of wind conditions and in a water depth of 4.0m, the BOVs are considerably reduced ($0.01ms^{-1}$ and $0.23ms^{-1}$, respectively). Possibly, wind conditions are so rarely strong enough to mobilise macroalgae at depths of 4m or more, that the processes of biological decay outstrip the processes of accumulation, whereas physical accumulation of algae can dominate decay at shallower depths.

It should also be noted that some of the strongest winds come from the south-west, and drive circulation patterns in Princess Royal Harbour which favour movement of suspended benthic algae towards the north-west and south-east ends of the Princess Royal Harbour basin where the heaviest algal accumulations have been observed (Hillman *et al*, 1991b). Wind-induced circulation currents, as indicated by the hydrodynamic modelling appear to be greater than, or comparable with the bottom orbital wave velocities.

7.5 Role of seagrass

Near the base of seagrass meadows, water movement is retarded. The seagrass beds therefore encourage a depositional environment for fine organic particulates. Nevertheless, even in very shallow water, appreciable currents can still be generated at the level of the seagrass canopy and above fully submerged meadows.

7.6 The influence of stratification on the contrasting ecological response of Princess Royal Harbour and Oyster Harbour

Oyster Harbour and Princess Royal Harbour are located on either side of the town of Albany, adjacent to King George Sound. The contrasting ecological responses of these harbours to nutrient inputs has been related to the relative influence of stratification and the consequent difference in hydrodynamic characteristics of these water bodies (D'Adamo, 1991; D'Adamo *et al* , 1992). Extensive seagrass dieback has occurred in both harbours, mainly due to shading and smothering by the macroalga *Cladophora sp.* and the growth of epiphytes on seagrass leaves. Oyster Harbour presently retains a greater relative percentage of its original seagrass biomass than Princess Royal Harbour. Oyster Harbour receives its nutrient loads via river flows, whereas the Princess Royal Harbour nutrient inputs are delivered in industrial, urban and limited rural discharges. Although average nutrient loadings into these systems have been similar, the amount of macroalgal biomass present in Princess Royal Harbour is an order of magnitude greater than in Oyster Harbour. This apparent anomaly is not completely explained by biological, chemical or photic factors. An important controlling factor appears to be the variable hydrodynamic characteristics of the two harbours.

Oyster Harbour is estuarine, being seasonally stratified in salinity by river flow. Wind-induced vertical mixing is restricted by the resulting density stratification, and nutrient-laden flood flows are exported as surface buoyant jets through the harbour mouth into King George Sound.

In contrast, Princess Royal Harbour receives little freshwater input, has greater exposure to winds and is typically well mixed by winds, wind-driven currents and tidal currents. Circulation is largely barotropic, residence times are relatively large and the availability of nutrients to benthic flora is high.

8. Conclusions and findings

8.1 Water structure in Princess Royal Harbour

Freshwater inputs to Princess Royal Harbour are low. Princess Royal Harbour generally exhibits weak, sub-basin scale horizontal and vertical density stratification. Theoretical analysis suggests that for a water body of the size and weak stratification generally exhibited by Princess Royal Harbour, moderate winds are typically able to induce vertical mixing over most of the harbour within several hours.

Salinity and temperature variations are maximal at the periphery of very shallow, intertidal margins in Princess Royal Harbour. On a few occasions only, following strong rainfall and runoff events from the small urban and rural catchment, was basin-scale stratification observed.

8.2 Hydrodynamic forcing agents

Tide and wind are the primary forces driving water movement in Princess Royal Harbour. Field measurements of Princess Royal Harbour water circulation show that the harbour responds barotropically to typical forcings, and displays circulation patterns largely as predicted by the hydrodynamic model. Horizontal density differences and baroclinic mechanisms may be important in driving water exchange between the shallows and the basin of Princess Royal Harbour and under strong winter runoff conditions, may influence the whole harbour.

8.3 Tidally-induced circulation

Water volumes of up to 30 million m^3 may enter or leave Princess Royal Harbour within eight to 16 hours on rising or falling tides, producing current speeds through the narrow Princess Royal Harbour entrance channel of up to $0.5ms^{-1}$, much greater than the average tidal current speeds across Princess Royal Harbour and King George Sound. The acceleration and momentum imparted to the water as it flows through this channel is an important factor in determining water exchange between Princess Royal Harbour and King George Sound, particularly under calm conditions.

In the absence of winds and during mean to spring flood tides, water from King George Sound is drawn in radially from a distance of approximately 1km outside the entrance channel, passes rapidly through the channel, initially shedding vortices into the harbour, and then jets narrowly (under its own momentum) a distance of up to 2.5km directly across Princess Royal Harbour, prior to undergoing clockwise circulation during the ebb tide. This promotes significant horizontal mixing over that area of Princess Royal Harbour where water depths are greater than 5m. Elsewhere in the harbour, tidal current speeds are very low, except across the shallow sandy sill at the outer edge of the western margin.

Likewise, on the ebb tide, water in Princess Royal Harbour converges radially toward the entrance channel from a distance of up to 1.8km, accelerates through the channel and then passes into King George Sound. Early in the ebb tide, the flow fans out broadly into King George Sound. As the water level falls more rapidly, outward-directed momentum increases and vortices (typically 500-1000m across) are shed into King George Sound on both sides of the channel axis (but more consistently and intensely on the north side). In particular, such vortices have been observed adjacent to the King Point wastewater outfall. Subsequently, a narrow tidal jet streams out across King George Sound. The remnants of this jet can be observed at some distance from the entrance channel for several hours after low water, while water close to the entrance channel again starts to converge on the harbour.

Some of the water which formed side vortices in King George Sound on the ebb tide remains sufficiently close to the harbour channel to re-enter Princess Royal Harbour on the subsequent flood tide. Since these vortices have been observed to form in the vicinity of the King Point wastewater outfall, some of the effluent from this outfall is likely to enter Princess Royal Harbour.

The tidal rise and fall of water levels within and outside Princess Royal Harbour are very similar. Hence, a widening or deepening of the existing entrance channel would not result in an increase of flow through the channel (because the tidal capacity of the harbour would remain unchanged). In fact the speed of water flowing through the channel would decrease. This may adversely affect the penetration of the jet flow and the net amount of exchange between these two water bodies.

8.4 Wind-driven circulation in Princess Royal Harbour

The action of wind stress on the harbour is an important agent of horizontal water movement. Wind-driven flows vary with depth. Surface water generally moves downwind at about 3% of the windspeed. Below the surface, water circulates about Princess Royal Harbour as horizontal gyres, which are controlled by the speed and direction of the wind and the alignment and depth of the harbour. These gyres have a down wind component in shallow water and an up-wind component in deeper water. The non-uniform, but relatively simple bathymetry and the alignment of Princess Royal Harbour with prevailing wind directions, favours the generation of horizontal wind-driven circulation currents.

Steady west to north winds generate one major anti-clockwise circulation gyre which occupies much of the harbour. East to south winds generate predominantly clockwise circulation. Under south-west winds, two major gyres are established (a clockwise gyre in the north-western half and an anticlockwise gyre in the south-eastern half of the harbour). For winds swinging within these respective direction ranges, the water movements will generally be consistent and cumulative. For winds swinging between these direction ranges, current directions may be decelerated or reversed, and net circulation limited.

8.5 Circulation under combined wind and tidal conditions

It takes only very moderate winds to modify the purely tidal circulation pattern within Princess Royal Harbour. For example, under north to west winds, the tidal jet streaming into the harbour on the flood tide is deflected to the right (along the length of the wharf area) as it becomes entrained into the anticlockwise wind-driven circulation. A portion of this newly introduced water penetrates so far into Princess Royal Harbour that it is retained there during the subsequent ebb tide, water leaving the harbour on the ebb is derived predominantly from the southern side of the entrance. For east to south winds, the flooding tidal jet is deflected to the left (flowing south-westward past Geak Point) and much of the ebbing water is derived from the north of the harbour in front of the wharf. The combined influence of wind and tide on the water movements is of great importance to the net water exchange and flushing from the harbour.

Likewise, wind-driven circulation in King George Sound can modify the tidal ebb jet flows emanating into the Sound and can influence the net water exchange between Princess Royal Harbour and the Sound. From field measurements it appears that south-west to south-south-east, or north-north-west to north-east winds are efficient in driving water circulation in the western portion of King George Sound. These directions are approximately parallel to the general coastal alignment of this part of the Sound. South-west to south-south-east winds induce marked water flow to the north (3-4km excursions observed) through Middleton Bay. To a lesser extent, north-north-west to north-east winds induce a southward flow of water.

8.6 The transport and flushing of pollutants

Floatable material or surface slicks move down wind at about 3% of the wind speed except when caught in strong tidal currents, e.g. in the entrance channel.

Dissolved or suspended pollutants become well mixed vertically within about 1km of the discharge point. These pollutants therefore have frequent contact with the bottom dwelling plants and animals. The transport of dissolved/suspended materials about Princess Royal Harbour is mainly influenced by wind-driven circulation gyres (down wind in shallow water and up wind in deeper water) and by tidal currents (closer to the mouth). The horizontal circulation induced by wind (and to a lesser extent tide and density forces) promotes broad horizontal mixing of these materials throughout Princess Royal Harbour.

The time to flush dissolved or suspended pollutant material from Princess Royal Harbour varies with season and location of the discharge. The winter range of effluent flushing times is narrow due to the efficiency of the wind-driven circulation gyres in mixing pollutant around the harbour as part of the flushing process. A typical 90% materials flushing time for Princess Royal Harbour is about 10-20 days. Such a flushing time is considerably larger than the timescale of nutrient uptake by macroalgae (Lavery and McComb, 1991) which is at most of order one day. This discrepancy between the timescales for hydrodynamic flushing and nutrient uptake by macroalgae is consistent with the observed low nutrient concentration status of the waters and the very large nutrient store accumulated in the macroalgae of Princess Royal Harbour.

The King Point treated effluent outfall is located adjacent to the area of intake of water from King George Sound to Princess Royal Harbour. Effluent from the King Point outfall may be partially entrained in a vortex (eddy) flow on ebb tide and this effluent may enter Princess Royal Harbour on the subsequent flood tide.

Likewise, some effluent from sources within the harbour may be initially flushed, and then drawn back into Princess Royal Harbour on the subsequent flood. However the existence of a narrow entrance channel, and the onset of the ebb tidal jet reduces the amount of this re-entry.

Under south-west to south-east winds effluent from King Point or Princess Royal Harbour may reach Middleton Bay and approach Middleton Beach. These conditions may also be those for minimal re-entry to Princess Royal Harbour.

8.7 The interaction of seagrass and algae with the hydrodynamics

Current speeds and wave-induced water speeds at the harbour bottom are generally weak in locations where the benthic algae are observed to accumulate.

Seagrass meadows provide resistance to flow and dissipate wave energy, providing a depositional environment, although water movement at the canopy may be significant.

8.8 Can increased pollutant flushing by the harbour be engineered?

Princess Royal Harbour is linked by a relatively short, narrow entrance channel to King George Sound and the ocean. Sea level variations with periods longer than a few hours are readily transmitted into Princess Royal Harbour with very little time lag, and the water level ranges within and outside the harbour are virtually identical. Hence, widening or deepening the existing entrance channel or opening a new one, would not necessarily lead to greater flushing. Such measures would lessen the extent and vigour of the tidal jet into Princess Royal Harbour and King George Sound and possibly reduce the flushing.

Deepening (dredging) shallower areas of the harbour may also reduce the flushing rate. A harbour with more uniform bathymetry would lead to a reduction in the strength of the wind-driven circulation, a weakening of horizontal mixing in the harbour, and hence a reduction in the flushing capacity of the harbour.

It is concluded from this hydrodynamic and pollutant transport study of Princess Royal Harbour, that the problems of the harbour can best be addressed by a policy of reduction or elimination of the pollutant source rather than some engineering method of increasing harbour flushing.

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Appendix 1

List of drogue tracking days

For future reference, Table A1 provides a complete list of the dates and time periods of all drogue tracking conducted within or immediately outside of Princess Royal Harbour, Albany, as part of this study. These data are held both by the Australian Surveying and Land Information Group (Perth Office) and the Environmental Protection Authority (Marine Impacts Branch).

Table A1: Dates and time periods of drogue tracking within or immediately outside of Princess Royal Harbour.

Date	Time Period	Location	Date	Time Period	Location
7/5/85	1229-2022	KGS	21/8/85	0821-1715	PRH
8/5/85	1128-1743	KGS	25-26/8/85	1707-0239	PRH
9/5/85	1135-2110	KGS	27-28/8/85	1730-0300	KGS
10/5/85	1244-2129	PRH	23-24/2/86	2300-0900	KGS
13/5/85	0849-1702	PRH	25/2/86	0940-1700	KGS
14/5/85	0915-1645	PRH	28/2/86	0943-1653	PRH
15/5/85	0921-1640	PRH	1/3/86	0800-1700	PRH
16/5/85	0910-1653	PRH	5/3/86	0730-1430	PRH
21/5/85	0256-0933	PRH	19/2/86	0624-1446	PRH
22/5/85	0304-1028	PRH	20/2/86	0911-1744	PRH
23/5/85	0316-1020	PRH/KGS	21/2/86	0702-2339	PRH
24/5/85	0317-1017	KGS	22/2/86	0045-0557	PRH
7/8/85	0819-1730	PRH	23/2/86	0000-2116	KGS
8/8/85	0829-1645	PRH	24/2/86	2304-0855	KGS
11/8/85/	1052-1747	PRH/KGS	28/2/86	0943-1653	PRH
14/8/85	0912-1854	KGS	1/3/86	0802-1706	KGS
20/8/85	0842-1738	PRH	5/3/86	0726-1434	PRH

Appendix 2

The hydrodynamic model

A two-dimensional numerical model described in Mills (1985) was used to simulate the hydrodynamics of Princess Royal Harbour under forcing by wind and tide. This model employed an explicit finite-difference numerical scheme to solve the depth-integrated, non-linear equations of motion for a well-mixed water body. A linear/quadratic relationship between bottom shear stress, $\underline{\tau} = (\tau_x, \tau_y)$ and the depth-averaged current velocity $\underline{v} = (u,v)$ was assumed (Hearn and Hunter, 1987) of the form:

$$\tau_x = -\rho\ C_D\ u\ MAX(u_f,\ (u^2+v^2)^{1/2})$$

$$\tau_y = -\rho\ C_D\ v\ MAX(u_f,\ (u^2+v^2)^{1/2})$$

where u_f, called the bottom friction scale velocity, is an rms estimate of speed near the sea bed for water motions which are present, but cannot be calculated by this model, e.g. wave motions. The friction law hence changes from linear to quadratic at $(u^2+v^2)^{1/2} = u_f$. Flooding and drying of the shallow banks of Princess Royal Harbour was represented by moveable model boundaries using the method of Flather and Heaps (1975).

The justification for applying this model to simulate the hydrodynamics of Princess Royal Harbour has been argued in the main report. To recapitulate, it has been shown firstly that typical winds are able to effect vertical mixing of the water column and secondly that the model is able to represent major aspects of the observed hydrodynamic response of the harbour, such as horizontal, wind-driven circulation gyres and the tidal flood-jet and ebb flow patterns.

A2.1 Hydrodynamic modelling procedure

The model was based on a 200m square grid chosen to cover Princess Royal Harbour and oriented with one set of grid lines parallel to the dredged shipping channel through the harbour entrance (172°N). Data input matrices (dimensions 39 x 33) describing coastal form and bathymetry were prepared from a 1:15000 scale chart (Public Works Department, WA OM 52923, 1981). Depth soundings are still unavailable for 6% ($2km^2$) of the total plan area of Princess Royal Harbour. In these mainly intertidal areas, depth estimates input to the model have been based on field observation and aerial photography of drying extent at times of known water level. Using this discretisation, the major bathymetric features of Princess Royal Harbour are well resolved.

The boundary of the Princess Royal Harbour model is closed (representing coastline) except for one open segment of three grid lengths across which flow enters and leaves the modelled area. This open boundary represents the section of the Princess Royal Harbour entrance channel with the smallest area. The distribution of water depths specified at the open model boundary is designed to represent a central 200m wide navigation channel of depth 12.5m and two shallower side areas, while preserving the total sectional area. The model sectional area used was $3.46 \times 10^3\ m^2$, (within 0.3% of the prototype sectional area).

The model calculates the time-varying field of motion induced in Princess Royal Harbour by introducing and abstracting water through the harbour entrance, i.e. by specifying volume fluxes across the open model boundary. The total volume flux rates through the entrance are derived by specifying a form for the water level (e[t]) variation and calculating increments of the Princess Royal Harbour tidal prism volume for successive time intervals, on the assumption that the water surface in Princess Royal Harbour is horizontal. The flooding and drying of intertidal margins causes the water surface area (A[e]) of Princess Royal Harbour to vary as a function of water level. The dependence of water surface area on water level is shown in Figure A2. Thus total water volume flux rate (Q[t]) may be calculated as:

$$Q(t) = A(e).\ de/dt$$

The water level data calculated by the model indicate that, for pure tidal forcing, the water surface of the harbour is virtually horizontal. This result is consistent with the assumption made to calculate the tidal prism and tidal discharge at the harbour entrance from a given vertical tide variation.

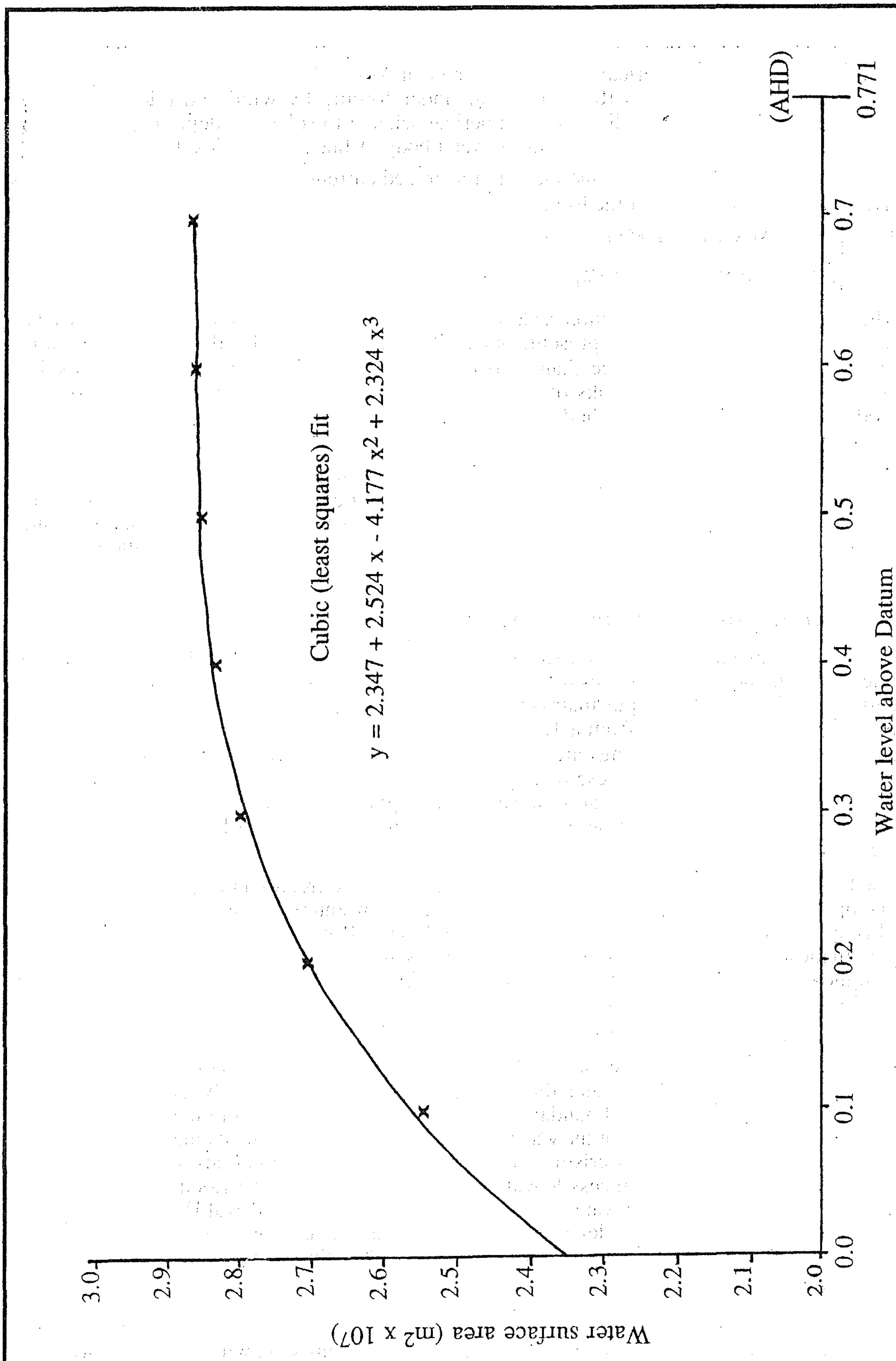

Figure A2: The dependence of Princess Royal Harbour water surface area on water level.

It is assumed that the lateral velocity profile across the entrance channel is uniform, and the total volume flux rate is distributed along the open boundary accordingly. Thus volume flux rates are specified continuously in time at the open boundary. Normal velocity components at the closed boundary are set to zero, a condition of no flow across coastlines. However the closed boundary is repositioned as necessary to account for flooding and drying in intertidal areas.

At the commencement of each model run the values of water surface elevation and current speed were set to describe a static water body with a horizontal surface.

Momentum advection effects were included in all internal velocity calculations in the model, except for calculations of u (the normal component of velocity) within one grid length of the open boundary.

In some computations local wind forcing was included together with the effects of flow through the harbour entrance. It was assumed that the indirect (external to the harbour) effects of observed wind and meteorology on Princess Royal Harbour were accounted for in the sea levels experienced at the harbour entrance and hence within the tidal prism volume and entrance flow estimates. Therefore this model was run only in hindcasting mode, i.e. using observed combinations of wind and water level data. It was assumed that wind-induced slope in Princess Royal Harbour did not introduce unacceptable error into tidal prism volume estimates although water level information was available at one point only. Mills and Brady (1985) gives estimates of water surface slope in Princess Royal Harbour in response to wind stress which support this assumption.

A numerical stability criterion (Courant *et al*, 1928) imposed an upper limiting value for the computational time step of 12.8s, corresponding to a maximum water depth of 12.5m. The value actually used in the model was 8s, so that 10800 model time steps represents one day.

The bottom friction scale velocity (u_f) was estimated on the assumption that surface gravity waves were the major hydrodynamic factor omitted from this model. Using linear wave theory, it was calculated that a wave of height 0.5m and period 4s would be associated with a velocity of about $0.1 ms^{-1}$ in a water depth of 3m.

A summary of model parameter values used is as follows:

Grid length	200 m
Time step	8 s
Coriolis parameter	$-0.0000837\ s^{-1}$
Bottom friction coefficient (C_D)	0.0025
Scale bottom friction speed	$0.1\ ms^{-1}$
Minimum depth used in stress terms	0.2 m
Drying coefficient (de/dx)	0.000025

A2.2 Hydrodynamic model performance

The model was run with a specification of volume flow rates at the open boundary appropriate to a pure sinusoidal tide in Princess Royal Harbour of period 12 hours and range 1 metre. Initial interest centred on the rate of convergence of the model results to a strictly periodic response. The model was run for four tidal cycles. Note that throughout this report, the figures presenting the hydrodynamic model vector outputs contain the parameter TR representing the time since the model was begun in terms of tidal cycles. For example, TR=1 is the end of the first 24 hour tidal cycle. Examination of detailed time-series of the depth-averaged velocity components at six selected locations showed that between the second and third tidal cycles, maximum deviations were 14% and between the third and fourth tidal cycles, maximum deviations were 1.4%. The maximum deviations occurred in sites of deep water, convergence was more rapid at shallow water sites. These results provided a guide for economising on further model run times while maintaining accuracy of the results.

An 'effective' Reynolds number R for the model may be defined by taking the ratio of one of the momentum advection terms to the bottom friction term (Hearn and Hunter, 1987).

$$R = (h/2C_D)\,(1/u^2)\,(du^2/dx) = h/(2.\ C_D\,X),$$

where the x-axis is along the jet, h is the water depth and X is a characteristic along-jet length scale. The axial velocity of the flood jet varies over a length scale of 2000m. Thus with a C_D = 0.0025, h = 10m, R = 1. For such a value of R, numerically induced features of the model flow field are expected to be small. The adopted grid resolution of 200m adequately defines the major flow features.

Appendix 3

Materials transport model

A two-dimensional Lagrangian particle-tracking technique (Hunter, 1987) was modified and used to model the dispersion of dissolved contaminant discharged at several locations in Princess Royal Harbour and to estimate pollutant flushing times for Princess Royal Harbour. This model simulates the fate of dissolved "contaminant" by tracking the movement and spread of an ensemble of discrete particles. Either an initial distribution of particles may be defined or particles may be introduced to the model at a specified rate and location to simulate a point source discharge of material. The depth-averaged current velocity results from the hydrodynamic model are used by the transport model to calculate the advection of the particles about the harbour. "Turbulent diffusion" of the particle clouds is treated with stochastic methods. Hence, pollutant transport simulations can be run for specific hydrodynamic forcing conditions of wind and sea level variation and with specific particle release points. Pollutant flushing times can be defined as the time taken to "lose" a given percentage of particles by export through the harbour mouth. Since the model open boundary is located across the harbour entrance channel, no allowance is made here for re-entry of particles to the harbour.

The Lagrangian transport model was used to simulate the spread and eventual exit from Princess Royal Harbour of particle streams released from specific points (representing the locations of industrial outfalls and drains into the harbour). A total of 1405 particles was released at a constant rate over a period of 24 hour (low water to low water), after which time the source of particles was turned off, but the evolution of the released particle trajectories continued to be calculated. The model results were analysed to determine the number of particles remaining in the harbour as a function of time and on this basis harbour flushing times were deduced.

An effective diffusion parameter, DIFF = 1 m^2s^{-1}, was set in the model. Lam *et al* (1984) show that this value is consistent with patch length scales of order 1km. The constant parameter value is consistent with Fickian diffusion.