The application of a three dimensional baroclinic model to the hydrodynamics and transport of coastal waters between Fremantle and Mandurah, Western Australia: the interconnectedness of the coastal zone.

A contribution to the Southern Metropolitan Coastal Waters Study 1991-1994

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Abstract

From about June to September each year strong riverine flows enter the Swan-Canning and Peel-Harvey estuarine systems, located on the southwest coast of Western Australia, and low salinity water is discharged from these estuaries to the adjacent marine waters, forming buoyant surface plumes. It is important to understand the direction and extent of transport, and rate of dilution of these plumes, since they carry loads of nutrients, fine particulates and other catchment-derived contaminants into the coastal waters and influence the hydrodynamics of the coastal zone.

This paper summarises the three-dimensional, numerical hydrodynamic modelling investigations of these plumes, conducted by the Department of Environmental Protection as part of its studies (from 1991-1994) into the marine ecology of Perth's southern coastal waters. The model results indicate that, within a few days, under favourable wind conditions, the Swan-Canning Estuary plume can influence many different parts of the southern metropolitan coastal waters, including Gage Roads, Owen Anchorage, Cockburn Sound, Sepia Depression, Warnbro Sound and the waters about Rottnest Island. Likewise, buoyant water discharged from the Peel-Harvey Estuary can be driven into Comet Bay, Warnbro Sound and Sepia Depression within 1-2 days under winds from the southwest quadrant, or driven off-shore under light to moderate southeasterly winds. These model results are consistent with the findings from shelf-scale and local-scale water quality studies that, in winter, estuarine outflows are a key factor in influencing the nearshore and inner shelf marine water quality off much of metropolitan Perth.

Buoyant plumes discharged from the Swan-Canning Estuary are driven (under most wind conditions) towards shallow nearshore areas which tend to be both biologically productive and sought after for multiple human uses. Episodic winds from the northerly quadrants in winter drive low salinity water discharged from the Swan-Canning Estuary southward. As a result of incursions of the estuarine plume into Cockburn Sound the salinity of the sound is lowered, causing a density difference between Cockburn Sound and the surrounding shelf waters which is one of the key determinants of the circulation and flushing regimes of the sound in winter. It has been shown that the Peel-Harvey Estuary plume can readily enter Warnbro Sound under southwesterly wind conditions which occur frequently throughout the year. Likewise, in winter, buoyant water can be driven out of the southern entrance of Cockburn Sound and, within 1-2 days, transported to Warnbro Sound and Comet Bay.

These results highlight the hydraulic interconnectedness between the estuaries, inner shelf and nearshore embayments and the need for coordinated marine monitoring at the appropriate spatial scales. They also point to the need for including marine ecosystem protection objectives in integrated catchment management programmes.

1. Introduction

From about June to September each year strong riverine flows enter the Swan-Canning and Peel-Harvey estuarine systems, located on the southwest coast of Western Australia, and low salinity water is discharged from these estuaries to the adjacent marine waters, forming buoyant surface plumes whose movement is strongly influenced by the wind (D'Adamo *et al.* 1995b, Mills *et al.* 1996). It is important to understand the direction, extent of transport, and rate of mixing of these plumes, since they carry loads of nutrients, fine particulates and other catchment-derived contaminants into the coastal waters and influence the hydrodynamics of the coastal zone.

This paper summarises the numerical hydrodynamic modelling investigations of these plumes conducted by the Department of Environmental Protection as part of its studies (from 1991-1994) into the marine ecology of Perth's southern coastal waters. The Southern Metropolitan Coastal Waters Study (SMCWS) aims to provide a better technical basis from which to manage the cumulative environmental impacts of present and predicted contaminants entering these waters (Simpson et al. 1993).

The hydrodynamic modelling was carried out in conjunction with water quality and oceanographic field studies (Cary *et al.* 1995; D'Adamo *et al.* 1995a, b; D'Adamo and Mills, 1995b; Mills *et al.* 1996) which were conducted under a range of meteorological, oceanographical and hydrological conditions. In the context of the SMCWS, the hydrodynamic modelling reported here aimed to increase our understanding of the major hydrodynamic transport pathways of water-borne substances, particularly those discharged to the coastal zone from catchments and estuaries.

The major focus of the hydrodynamic modelling effort has been on the series of embayments, basins and channels which comprise the SMCWS nearshore area. 'Local-scale' model domains extending to about 20 km offshore were established to encompass these water bodies and to include outflows from the Swan-Canning and the Peel-Harvey estuaries.

In this report, the bathymetric and hydrodynamic characteristics of the study area are summarised in Section 2, the hydrodynamic model is described in Section 3 and the implementation of the model to the study area is set out in Section 4. Section 5 presents model results for the transport of the estuarine plume from the Swan-Canning estuarine system under a range of wind forcing conditions and Section 6 compares field data sets of plume disposition with model simulations under similar forcing conditions. Section 7 presents the results of simulations of the wind-driven plume from the Peel-Harvey estuarine system (including simulations for the case where the estuary was hypersaline). Section 8 examines linkages between Cockburn Sound and Warnbro Sound.

2. Description of the study area

Bathymetry

The study area extends longshore from Trigg to Tim's Thicket and about 20 km offshore (westward) from the mainland coast beyond the 30 m bathymetric contour (Figure 1, Figure 2). This area contains the sheltered embayments of Cockburn Sound and Warnbro Sound, the semi-enclosed waters of Owen Anchorage, Gage Roads and Comet Bay, the channel-like Sepia Depression to the west of Garden Island, and the open waters of the inner-continental shelf. Cockburn and Warnbro Sounds have central basins 15-20 m deep and are bordered by shallow banks and sills. Owen Anchorage is a smaller basin, up to 12 m deep, and is bounded by the submerged Parmelia Bank to the south, Success Bank to the north and the partially emergent Garden Island Ridge System to the west. Comet Bay, south of Warnbro Sound, is a broad expanse of shallow water ranging in depth from 5 to 15 m and bounded to seaward by the Murray Reefs.

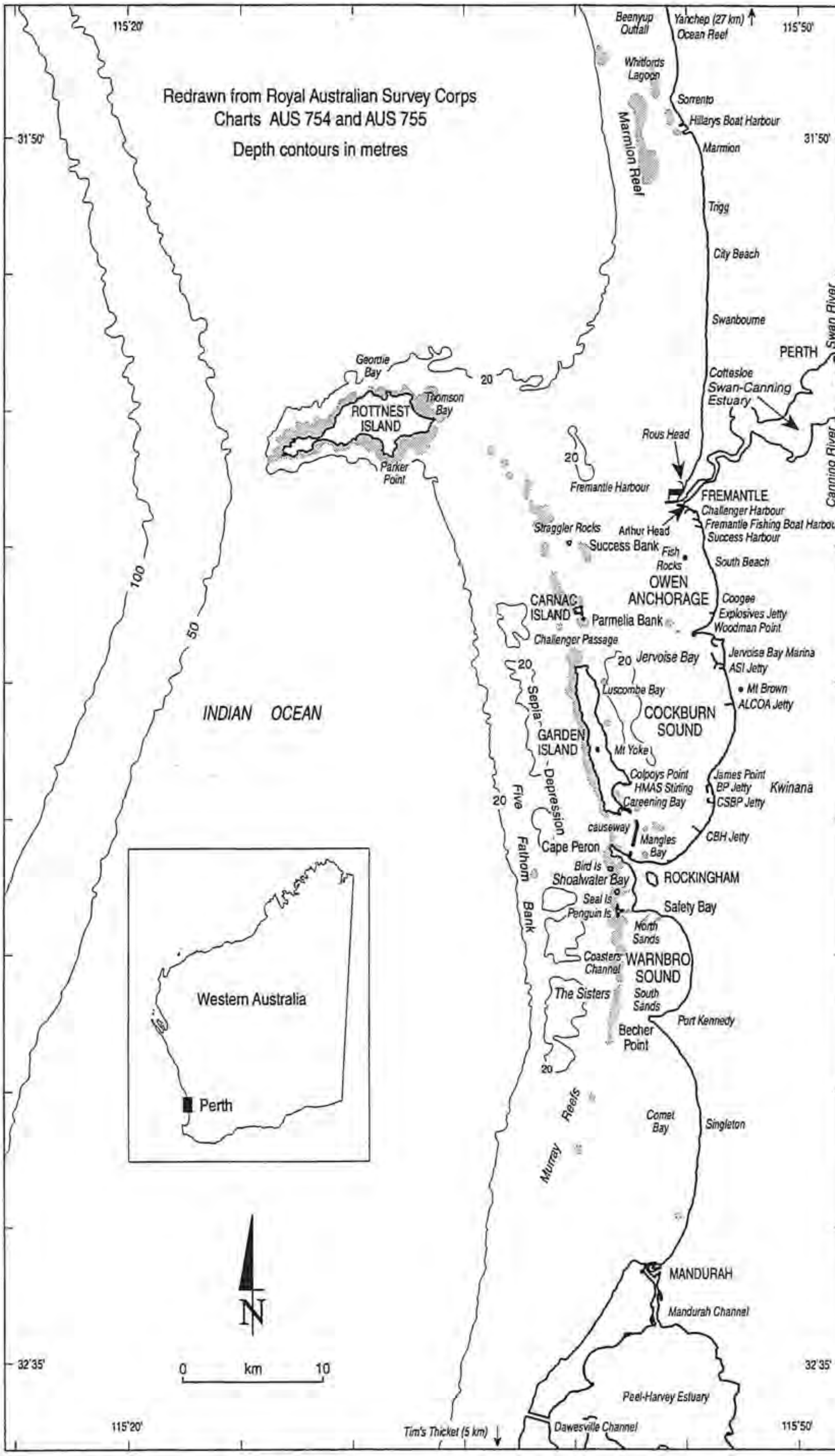

Figure 1. Location map of the study area.

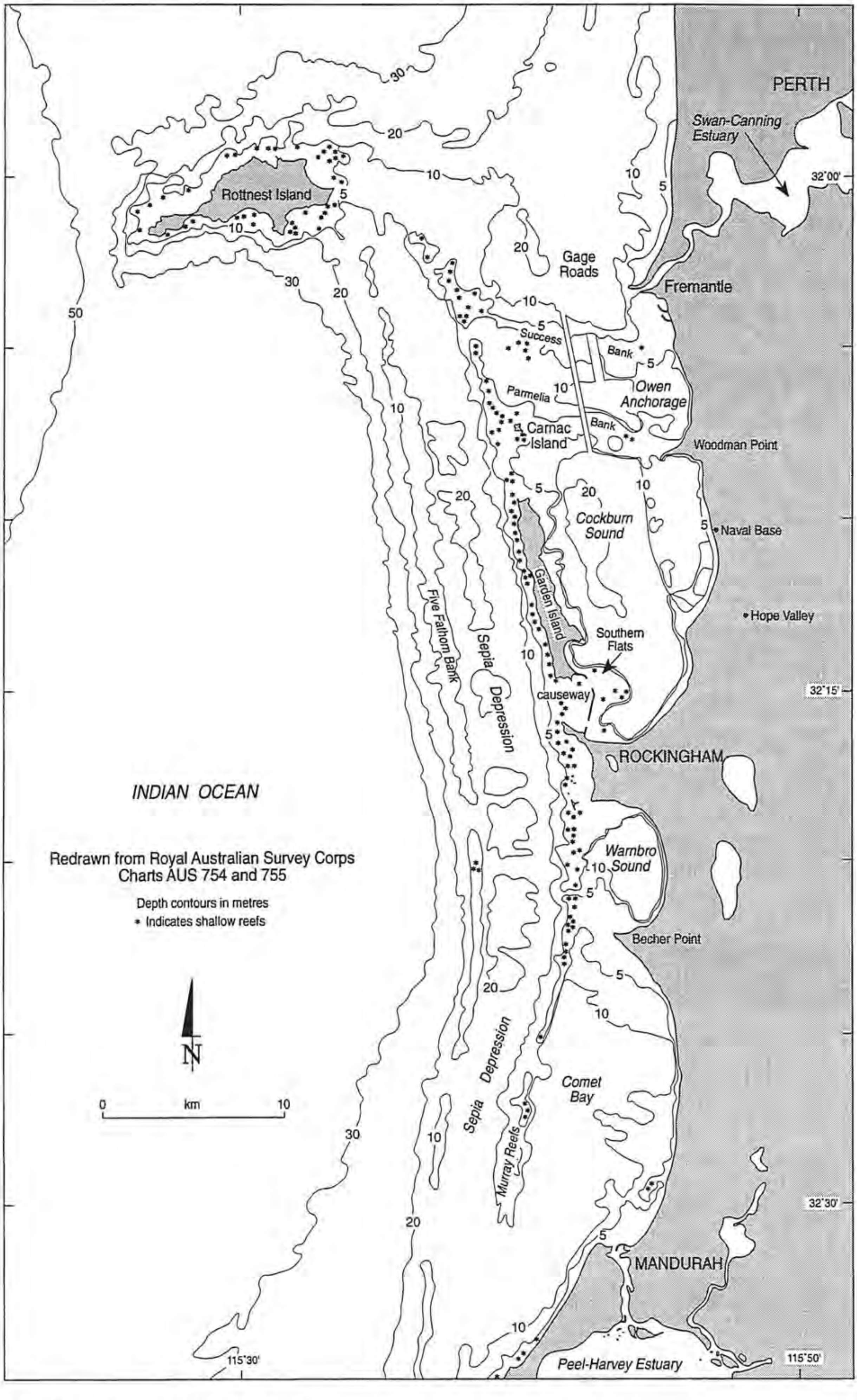

Figure 2. Bathymetry of the study area.

Sepia Depression is a long-shore trough 15-22 m deep and 5 km wide, situated between Garden Island and Five Fathom Bank to the west. The area beyond Sepia Depression includes the inner and mid-continental shelf and is more exposed to ocean swell.

Meteorology

The synoptic-scale weather patterns of the region are controlled by the migration of the anticyclonic belt from about 40 ° S in January to 30 ° S in July. This belt rotates eastward around the globe and results in synoptic variations in the barometric pressure field at periods of about 7-10 days, with synoptic weather patterns broadly reflecting this periodicity.

From about October to March stable anticyclonic pressure cells produce a predominantly easterly airflow over southwest Australia. From June to September the anticyclonic pressure systems and accompanying westerly winds (the roaring forties) are periodically displaced by low pressure cyclonic systems that move rapidly eastwards bringing strong winds (~ 20 m s^{-1}) and rain. Through much of the year local diurnal heating and cooling along the coastline results in a land-sea breeze cycle which is superimposed on the regional pattern, most noticeably in summer. Wind speeds in the Perth region are generally between about 5 and 15 m s^{-1}. Sea-breeze winds from the southwest quadrant occur on over 250 days each year although the strongest sea-breezes (10-15 m s^{-1}) occur mainly during the mid-spring to summer period (Hearn, 1991). Apart from during storms (> 10 m s^{-1}), the wind field becomes weaker and more variable throughout autumn and winter.

The annual average rainfall for the Perth region is about 900 mm with over 80 % occurring from May to September. The freshwater discharge patterns from the estuaries follow that of rainfall, but with a lag of about 1 month. The annual average evaporation is about 1700 mm with maximum and minimum rates of about 9 mm d^{-1} and 2 mm d^{-1} occurring in January and June, respectively.

Tides and barometrically forced water level variations

The tides of southwest Australia are relatively small and mainly diurnal. The predicted astronomical tidal range at Fremantle varies from about 0.1 to 0.9 m (Department of Defence, 1994) and the annual mean range is about 0.5 m (Hearn, 1991). Tidal currents for the Perth shelf are typically less than about 0.02 m s^{-1} (Steedman and Craig, 1983; Hearn *et al.* 1985; van Senden, 1991; Pattiaratchi *et al.* 1995).

Variations from predicted astronomical tide heights are mainly due to barometric pressure variations and wind effects. In combination, these meteorological effects can generally alter the water level by up to about 0.3 m during synoptic cycles. During the more infrequent passage (usually less than once per year) of tropical cyclonic depressions down the southwest coast the relatively strong pressure changes and winds can alter the coastal water level by up to about 1-2 m (Fandry *et al.* 1984; Hodgkin and Di Lollo, 1958).

Low frequency oscillations of water level along the coast of Western Australia have characteristic periods of 5-10 days and ranges of 0.1-0.3 m (see Webster, 1983; Hamon, 1966; Harrison, 1983). It is believed that low frequency oscillations could cause currents of order 0.01-0.1 m s^{-1} in the shelf zone off Perth (Hearn, 1991; van Senden, 1991).

Local and regional scale wind-driven circulation and the influence of the Leeuwin Current

The Leeuwin Current typically flows over the outer continental shelf and slope as a warm, low salinity tropical mass, driven by a north to south steric height gradient (Godfrey and Ridgeway, 1985). It is strongest from about March/April to September/October, and is weakened in spring/summer primarily in response to the strength of opposing south-southwesterly winds (Smith *et al.* 1991). The eastern edge of the Leeuwin Current water mass can approach the nearshore zone as a strong temperature/density front and influence the transport of inner shelf waters (Mills *et al.* 1996).

The near-shore shelf currents have typical speeds of order 0.1 m s^{-1} (see Hearn, 1991; Steedman and Associates, 1981; Pattiaratchi *et al.* 1995). They are primarily wind-driven and bathymetrically controlled, with secondary influences from long-shelf pressure gradients and density effects. In winter, current reversals occur typically at 3 to 5 day intervals, mainly in association with major wind shifts. In summer, the currents are predominantly northward, in response to prevailing winds from the southerly quadrants.

The dynamical influence of the earth's rotation is equivalent to an additional force acting perpendicularly to the direction of water movement. If this 'force' is not balanced, the flow direction will be significantly deviated in the anti-clockwise sense (in the southern hemisphere) after a time equivalent to the inertial period. At the latitude of Perth this is approximately one day. For water current speeds of order 0.1 m s^{-1}, typical of the study area, rotational effects become significant in unstratified water bodies which have horizontal dimensions of several kilometres or more. In such cases the Rossby number (Csanady, 1982) is less than one.

The combined presence of vertical density stratification and rotation introduces another dynamical length scale, the baroclinic radius of deformation (Csanady, 1982), which is in the range 1-3 km in Perth's nearshore coastal waters. The effects of rotation on the response of the density structure can be expected to be significant at these spatial scales.

3. Hydrodynamic model

3.1 Model requirements

The hydrodynamic modelling component of the SMCWS was based on reviews of the local and regional oceanography (Hearn, 1991; D'Adamo, 1992), the findings of the SMCWS oceanography characterisation phase (D'Adamo and Mills, 1995a, b; D'Adamo *et al.* 1995a, b; Mills *et al.* 1996) and on a review of available models. The reviews and characterisation confirmed the importance of wind as a primary driving force for the currents and highlighted the fine balance existing in the study region between natural stabilising processes that cause lighter water to move over or form above heavier water (e.g. river outflow and surface heating) and destabilising processes, such as turbulent mixing by wind stress or penetrative convection due to surface heat loss. The characterisation also suggested the significance of the earth's rotation at basin-scale and shelf-scale, and demonstrated the essentially three-dimensional and time-dependent nature of the water circulation and mixing regimes.

The hydrodynamic model was therefore required to be three-dimensional, time-dependent, and to be able to simulate responses to a wide range of forcings including imposed (meso-scale or regional) horizontal pressure gradients, tidal forcings, wind stress, horizontal buoyancy fluxes (from estuaries), vertical buoyancy flux (from air/sea transfers of heat and water), local pressure gradients (due to water surface slopes and horizontal density gradients set up within the study area), bottom frictional stresses and the effects of the earth's rotation. The model needed to take account of the relatively complex bathymetry of the study area and to be able to simulate a range of barotropic and baroclinic mechanisms, with realistic vertical and horizontal structure in water movement and water density, and realistic vertical mixing.

Three-dimensional baroclinic modelling techniques are now sufficiently advanced (Spaulding *et al.* 1992) that these models may be used in conjunction with appropriate field measurements to investigate the water circulation and hydrodynamic transport of substances in coastal water bodies under a broad range of meteorological and oceanographical conditions.

3.2 Description of the model

The *Princeton Ocean Model*, also known as the 'Blumberg-Mellor Model' (Blumberg and Mellor, 1980, 1987; Mellor, 1993), was chosen for application to the SMCWS. Over recent years this model has undergone development and successful application to diverse regions such as Chesapeake Bay, the Mid-Atlantic Bight, the Gulf of Mexico, the Great Lakes, and the east and south coasts of Australia.

This time-dependent, fully three-dimensional model numerically solves the non-linear primitive equations for the conservation of mass, momentum, salt and heat. The model computes density distribution from the modelled seawater temperature, salinity and pressure fields using an equation of state. Horizontal density gradients give rise to baroclinic forcings which feed back into the momentum balance. Vertical mixing in the model is determined by a turbulence-closure sub-model (Mellor and Yamada, 1982) which takes into account the role of vertical density gradients and water column stability. The model utilises a sigma coordinates system (Phillips, 1957) in which the vertical coordinate is scaled to water depth. In addition to three-dimensional simulations, the model can also be used in two-dimensional (depth-averaged) form.

The version of the Princeton Ocean Model used here is as described in Mellor (1993), but with the original Fortran computer code modularised and rewritten in the C language by Herzfeld (1995), and with additional data management and post processing routines developed during the SMCWS (Mills and Essers, 1995). The C language version of the model incorporates a range of open boundary conditions and employs the positive definite advection algorithm of Smolarkiewicz and Clark (1986). The far-field transport of effluent plumes from estuaries and ocean outfalls has been simulated in the model by introducing point sources of volume, heat and salt, following the method of Lazure and Salomon (1991).

4. Hydrodynamic modelling of waters between Fremantle and Mandurah

4.1 Aims

The nearshore marine waters of Perth's southern region include a series of partially-enclosed basins and channels, including Owen Anchorage, Cockburn Sound, Warnbro Sound, Comet Bay and the Sepia Depression (Figures 1 and 2). The Swan-Canning and the Peel-Harvey estuarine systems both discharge to this region. The aim of the modelling was to determine the spatial and temporal scales of the hydrodynamic transport in the region and to investigate the trajectories of plumes from these estuaries under a variety of forcing conditions.

4.2 Model domains, grids and bathymetry

Two model domains were used for the nearshore modelling of the southern metropolitan coastal waters, a northern domain and a southern domain. The northern model domain (Figure 3) extends 60 km long-shore, from City Beach in the north to mid Comet Bay in the south, and 23 km offshore, from the mainland coast to Rottnest Island and the vicinity of the 35 m depth contour. The maximum depth in the northern model domain is 39 m.

The southern model domain (Figure 4) extends 63 km long-shore, from Owen Anchorage in the north to Tim's Thickett in the south (about 8 km south of Dawesville) and 29 km offshore of the mainland coast to a maximum depth of 44 m.

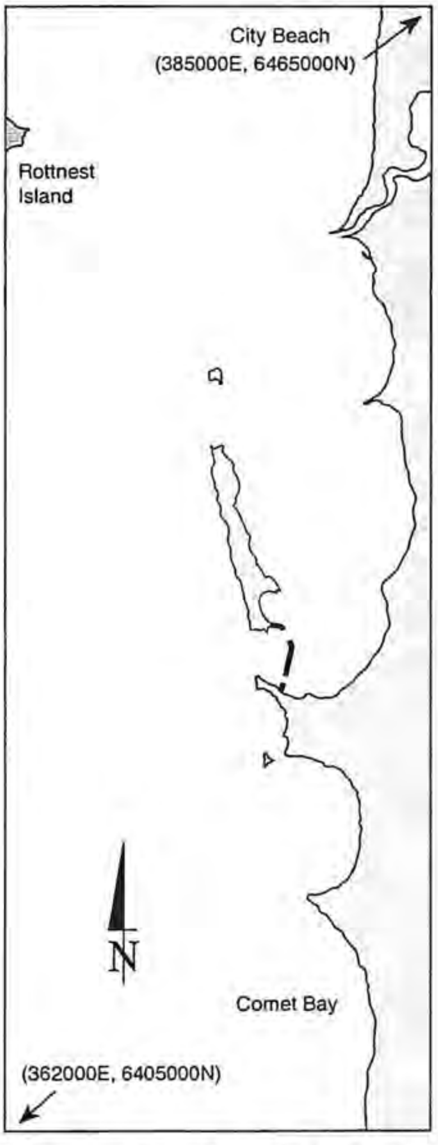

Figure 3. Northern domain for the hydrodynamic model simulations.

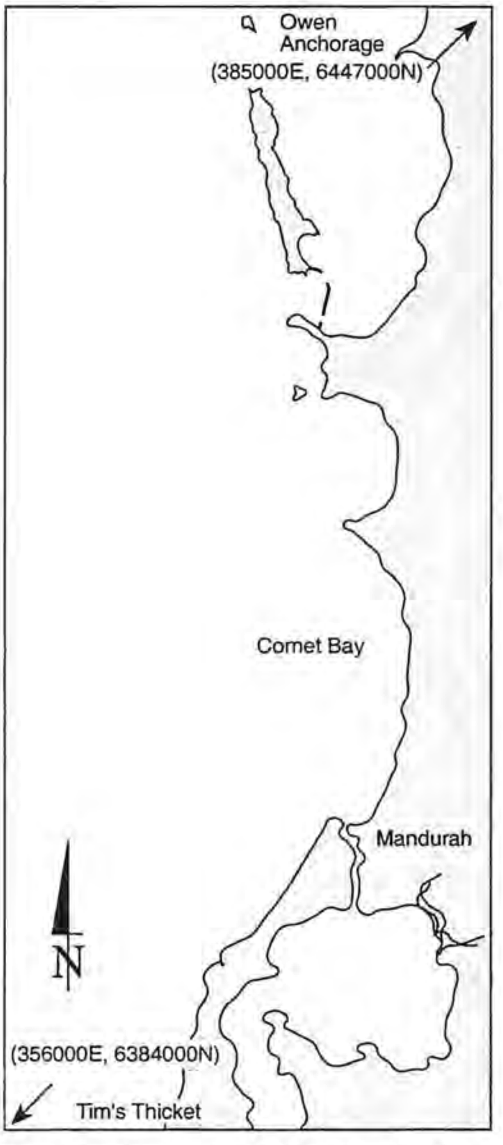

Figure 4. Southern domain for the hydrodynamic model simulations.

In each case the model was applied to a grid system which divides these domain areas into 500 m square cells. This grid is sufficient to spatially resolve important hydrodynamic boundary features, such as upwelling/downwelling zones and coastally-attached buoyant plumes, which have widths that scale with the baroclinic radius of deformation (typically about 1-3 km for these waters). The coastline and bathymetry of the area are also satisfactorily represented in the main, with a few exceptions. In particular, it should be noted that the 200 m wide shipping channel through Parmelia and Success banks is not resolved. The cross-sectional flow areas of the two bridge openings in the causeway at the southern entrance to Cockburn Sound have been correctly specified within the grid by slightly adjusting the water depth of these openings. Finer grid resolution would have been desirable, however it would have led to impracticably large computing times for each simulation, given the computing resources available. It was deemed equally important for the model to encompass the major bathymetric features in the areas surrounding the coastal embayments, including the islands, reefs and banks, and to remove open boundary effects away from the areas of principal interest. Hence the above balance was struck between spatial resolution and model domain area.

The vertical discretisation used for these simulations consisted of 12 sigma levels, forming 11 layers, two thinner ones near the water surface, and near the sea-bed, and the remaining seven layers of equal thickness, as shown in Table 1. Implemented in this way, the model was used to investigate the three-dimensional hydrodynamic response of the region to a range of external forcings, including surface wind stress, regional sea level gradient, buoyancy inputs from rivers and estuaries, and the mean seasonal density differences between shelf and embayment waters.

Table 1. Levels of the model sigma surfaces and thicknesses of the model sigma layers (expressed as fractions of the local depth of the water column). In sigma units, the sea surface level is denoted as 0.0 and the sea bed level as -1.0.

Sigma level or sigma layer number	Sigma surface level	Fractional thickness of sigma layer
1	0.000	0.056
2	-0.056	0.056
3	-0.111	0.111
4	-0.222	0.111
5	-0.333	0.111
6	-0.444	0.111
7	-0.556	0.111
8	-0.667	0.111
9	-0.778	0.111
10	-0.889	0.056
11	-0.944	0.056
12	-1.000	-

The model representation of the bathymetry was obtained from the hydrographic survey data base of the Western Australian Department of Transport. For each 500 m square model grid cell, these data were spatially averaged and then referenced to mean sea level using the difference between chart datum and mean sea level as determined at the Fremantle permanent tide gauge.

4.3 Model initialisation, forcings and boundary conditions

Each model run was started from an initial state of rest with the water surface at mean sea level. Unless otherwise stated, the initial salinity and temperature fields were set as constants throughout the model domain to represent an initially homogeneous ocean.

Wind stress was applied uniformly across the model domain and was either held temporally constant or else derived from half-hourly time-series data for winds recorded at a nearby coastal location, using the quadratic formula given in Fischer *et al.* (1979). A long-shelf pressure gradient of order 10^{-7} was applied to account for observed residual currents in a southward direction in winter.

The effect of the earth's rotation was included through the specification of the Coriolis parameter for latitude 32°S.

Following the approach of Lazure and Salomon (1991) the buoyant estuarine discharge was represented in the model as sources of volume and buoyancy introduced at the water surface of specified model grid cells. No additional horizontal momentum was introduced. Salinity (not temperature) and flow rate were used to represent the fresh water load corresponding to the simulated buoyant discharge. During the course of the simulation ambient salinity stratification (both horizontal and vertical) developed in the model domain and salinity deficit (relative to undiluted seawater) acted as an unambiguous tracer of discharged river water.

This approach recognises that the plume behaviour begins to be dominated by the buoyancy flux (rather than its discharge of momentum) at locations very close to the estuary mouth. Dimensional considerations suggest that the distance from the estuary mouth to the virtual origin of the buoyant plume scales with $M_0^{3/4}/B_0^{1/2}$, where M_0 is the exit momentum flux and B_0 is the exit buoyancy flux (see Fischer *et al.* 1979) and this has been verified in the laboratory by Chu and Baddour (1984) and in the field by Luketina and Imberger (1987). For typical discharges from the Swan-Canning and Peel-Harvey estuaries, it can be shown that the virtual origin of the buoyant plume is located within 10 - 100 m of the estuary mouths. Hence, the influence of the buoyancy flux becomes dominant over the momentum flux within one grid cell from the mouth. Rather than model the momentum dominated part of the discharge explicitly, the source of buoyancy and volume has been distributed over 4 (2 x 2) cells, which is still a very localised source area compared to the overall model domain.

The boundary conditions used for these model runs are set out in Table 2. The formulation of each of these boundary conditions (including the 'user defined' open boundary condition) is documented in Herzfeld (1995).

Table 2. Boundary condition settings at the open boundaries of the model.

Model Parameter	Open Boundary Condition Settings Western Boundary	Northern Boundary	Southern Boundary
elevation	Orlanski radiation	Orlanski radiation	Orlanski radiation
external velocity (normal)	User defined	User defined	User defined
external velocity (parallel)	Orlanski radiation	Orlanski radiation	Orlanski radiation
internal velocity (normal)	User defined	User defined	User defined
internal velocity (parallel)	Orlanski radiation	Orlanski radiation	Orlanski radiation
temperature	Upstream advection	Upstream advection	Upstream advection
salinity	Upstream advection	Upstream advection	Upstream advection

Tidal effects have been omitted from the modelling simulations discussed in this report. This can be justified over most of the model domain, where tidal currents are typically of order 0.01 m s^{-1} and advection length scales over a diurnal period are of order 1 km only. However, in some more constricted areas, such as in the vicinity of the bridge openings through the Causeway at the southern entrance to Cockburn Sound, significantly stronger tidal currents can occur, and water exchange, induced by these oscillatory tidal currents may be locally significant. Furthermore, the model does not capture the tidal ebb and flood currents at the entrance to the estuary and their role in generating 'pulses' of buoyant estuarine discharge. Notwithstanding these limitations, it will be shown that the model results presented in this report are generally consistent with the far-field behaviour of discharged estuarine plumes as determined from field measurements and observations under a range of meteorological conditions.

The model was set to run with an external mode time step of 9 seconds and an internal mode time step of 180 seconds. A list of other model run parameter settings is given in Appendix 1.

4.4 Model validation

Mills and D'Adamo (1995) presented the results of a model validation exercise for the northern grid. The model satisfactorily hindcast the measured currents from mooring sites in eastern Cockburn Sound and in Sepia Depression.

Furthermore, the model simulations of estuarine plume transport were compared, wherever possible, with relevant field measurements of water salinity and density structures, or water quality attributes (e.g. measured nutrient, chlorophyll-*a* and plankton distributions). Remote sensing observations of water colour and plankton distributions were also used to verify that the model was representing the main features of the transport of these estuarine waters. These comparisons are presented and discussed in Section 6.

5. Investigation of the Swan-Canning Estuary outflow into marine waters

5.1 Introduction

From about June to September each year strong riverine flows enter the Swan-Canning Estuary and low salinity water is discharged from the estuary to the coastal waters, forming buoyant surface plumes whose movement is strongly influenced by the wind (D'Adamo *et al.* 1995b, Mills *et al.* 1996).

A series of three-dimensional, baroclinic model simulations was conducted to investigate wind-driven, far-field transport of the buoyant Swan-Canning Estuary plume. Different wind conditions were used for each simulation, but the estuarine discharge rate, based on a freshwater flow of 60 m^3 s^{-1}, was held constant across all simulations. The simulations were initialised with no stratification in the receiving marine waters, however a stratification field developed in the course of the simulations as a result of the influx of low salinity water. The model results for each wind condition are presented in Figure 5 and discussed in the following sections.

Past field observations, reviewed in Hearn (1991) and D'Adamo (1992), indicate that the plume from the Swan-Canning estuary could extend into Owen Anchorage, Cockburn Sound, Sepia Depression and Warnbro Sound. The simulation results provide a systematic understanding of the influence of wind on plume transport and show that the model is able to reproduce major transport pathways of the plume.

5.2 Transport of Swan-Canning Estuary water into Cockburn Sound

The modelling predicts that northeasterly, northerly and northwesterly winds transport Swan-Canning estuarine water into Cockburn Sound as a surface buoyant plume, and that this occurs typically within 1.5 days of the commencement of favourable wind conditions.

Under northeasterly wind, low salinity water enters Cockburn Sound across the whole width of its northern entrance (Figure 5a), and within Cockburn Sound the buoyant plume tends to the eastern side of the deep basin. A vertical salinity section across the sound (Figure 6a) confirms that the southward-moving low-salinity plume is deepest over the eastern side of the basin. The northeasterly wind also forces the buoyant plume through Challenger Passage into Sepia Depression, where it is driven southward next to the west coast of Garden Island. The earth's rotation plays a significant role in these dynamics, deviating water to the left of the wind direction.

Under northerly and northwesterly winds, the discharged estuarine water is transported southward as a deep narrow plume attached to the mainland coast (Figures 5b and c, respectively). Once within Cockburn Sound the plume continues to extend southward and its low salinity water inundates the seabed of the eastern margin of the sound, as shown by the vertical salinity structure (Figure 6b).

Under westerly wind, the estuarine plume is confined to within 3-5 km of the coastline (Figure 5d). The plume extends both to the north and south of the point of discharge, and reaches the northeast corner of Cockburn Sound in about 1.5 days. The westerly wind forces downwelling of buoyant plume water against the mainland coast and induces a steeply-inclined front between the plume and adjacent ambient water.

5.3 Northward transport of Swan-Canning Estuary water

Under southwesterly winds the plume is driven northward in contact with the mainland coast (Figure 5e). The plume has a strong frontal boundary to the south and the west. Cross-sections of salinity show strong vertical gradients near the base of the plume at depths of less than 10 m.

Under southerly winds, the plume is driven to the north-northwest (Figure 5f) which is to the left of the wind stress direction due to deviation by the Coriolis force. The plume broadens with distance from the source and is essentially detached from the seabed if water depths are greater than about 8 m.

5.4 Offshore transport of Swan-Canning Estuary water

A southeasterly wind can drive buoyant plume water directly offshore, in a westerly direction (Figure 5g). The plume has a strong surface front on the southern side. A vertical section of salinity along the axis of the plume (Figure 6c) indicates that it is a buoyant surface feature, mainly detached from the seabed. However the model predicts that the plume undergoes significant local deepening on the upstream side of banks and reefs, exposing them to lower salinity water to depths of about 15 m. The hydraulic conditions for deepening of buoyant plumes in the presence of banks and sills has been further investigated by Chao and Paluszkiewicz (1991).

5.5 Transport of Swan-Canning Estuary water to Sepia Depression and thence southward

Under an easterly wind the estuarine plume extends southwest and reaches Carnac Island and the northern end of Garden Island within one day (Figure 5h). Some buoyant water enters into northwest Cockburn Sound. In the main, however, the plume moves into Sepia Depression and is transported southward. Cross-shelf vertical sections of salinity show that the southward moving plume remains attached to the west coast of Garden Island (Figure 6d).

As discussed above (Section 5.2), northeasterly wind drives low salinity water past the northern end of Garden Island and thence southward along Sepia Depression, as well as directly into Cockburn Sound (Figure 5a).

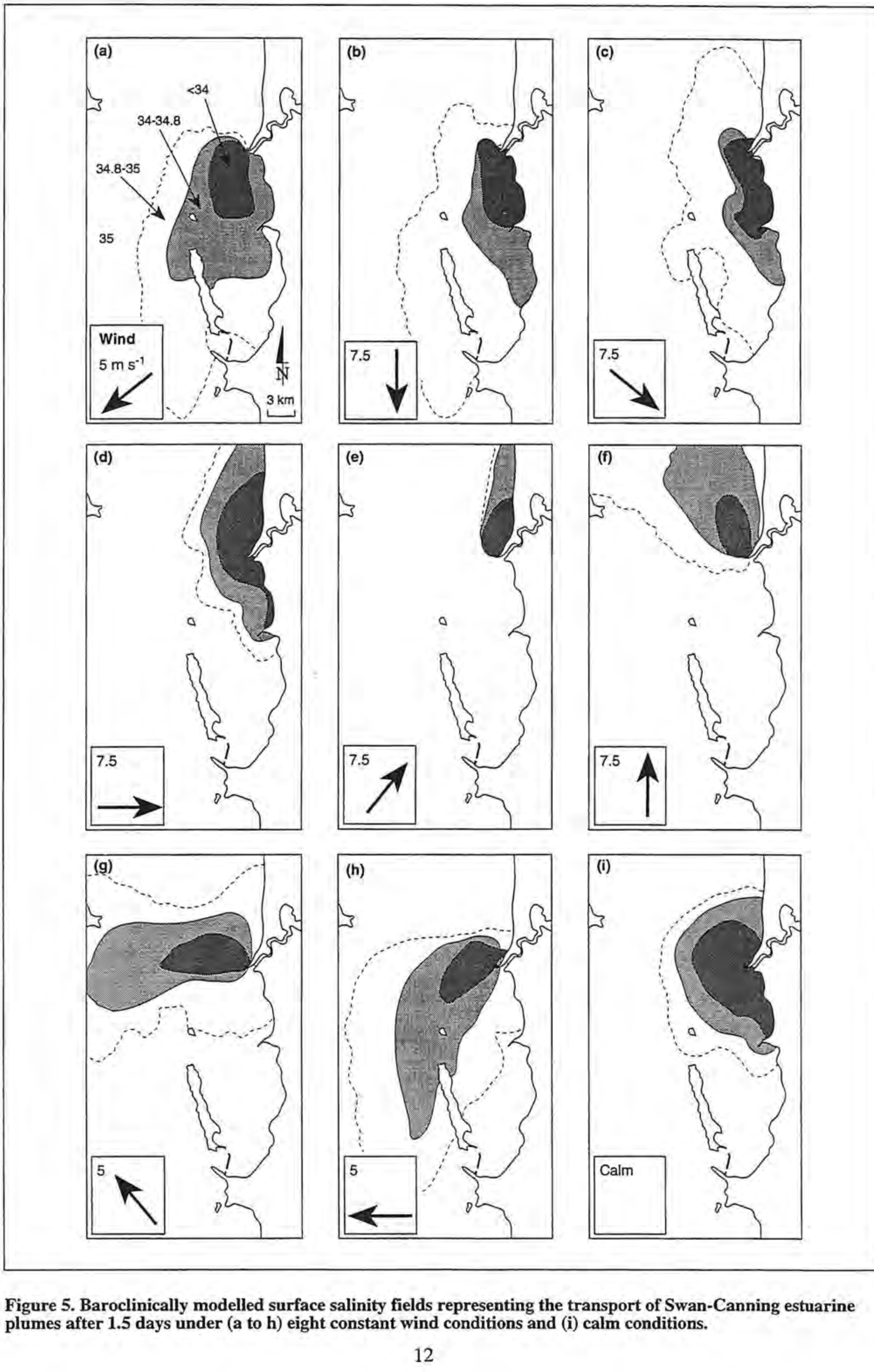

Figure 5. Baroclinically modelled surface salinity fields representing the transport of Swan-Canning estuarine plumes after 1.5 days under (a to h) eight constant wind conditions and (i) calm conditions.

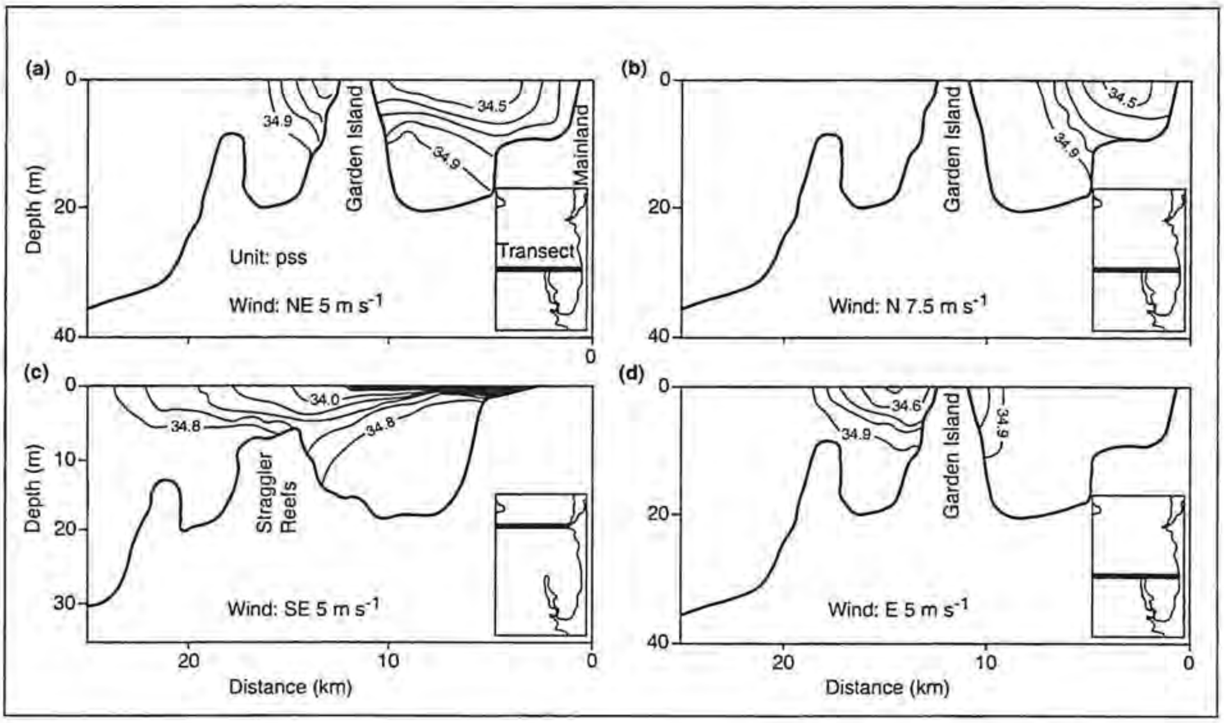

Figure 6. Baroclinically modelled vertical salinity sections through the Swan-Canning estuarine plume after 1.5 days under four (a to d) constant wind conditions.

5.6 Transport of Swan-Canning Estuary water under calm conditions

Under calm conditions the low salinity plume initially spreads radially due to its buoyancy. After about one day, when the plume has developed a horizontal scale comparable to the baroclinic radius of deformation (1-3 km), the plume water tends to circulate anticlockwise about the source under the influence of the earth's rotation. To the south of Fremantle, this circulation is blocked by the mainland coast, and the plume water is forced to flow southward as a boundary current (Figure 5i). It takes about 2 days for plume water to enter the northeast corner of Cockburn Sound, and thereafter it continues to propagate southward along the eastern margin of the sound.

5.7 Transport of Swan-Canning Estuary water under variable wind conditions

The transport of the buoyant Swan-Canning estuary plume was simulated using local wind data for the period 9-18 August 1991 (Figure 7a and b) during which time the wind veered anticlockwise from southeasterly through to westerly, with intervening strong northwesterly winds from 16-18 August. The simulation proceeded from an initial, specified salinity field (based on field data, and shown as Figure 8 of Mills and D'Adamo, 1995) with lower salinity water in Cockburn Sound relative to surrounding shelf water. Output from this simulation is presented for comparison with field data collected on 16 August.

By midday of 16 August 1991, that is 7.5 days after the start of the simulation, the modelled plume extended west to southwest past the northern tip of Garden Island, and southward along Sepia Depression as far as the entrance to Warnbro Sound (Figure 8a). This followed a period of easterly to northerly wind during the preceding 30 hours.

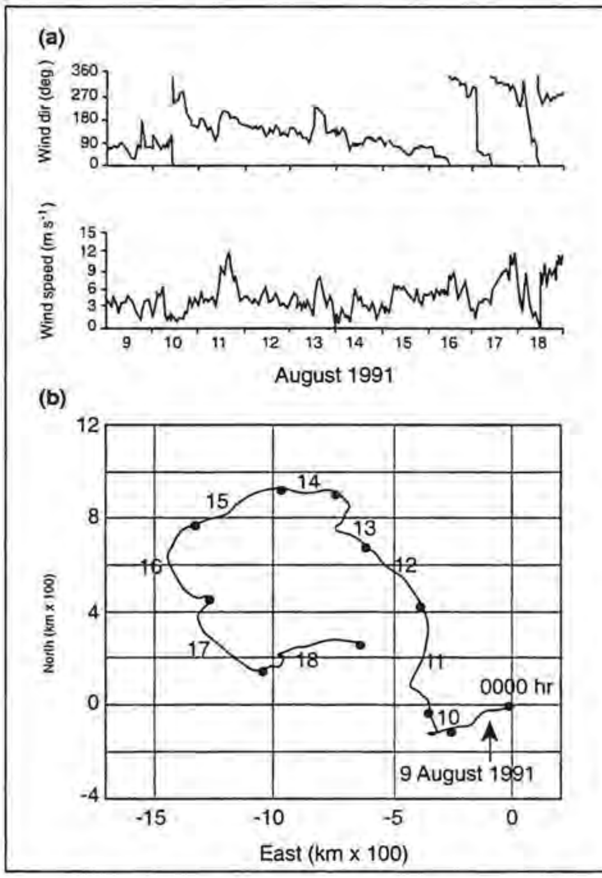

Figure 7. Wind data input for the baroclinic modelling of the transport of the Swan-Canning estuarine plume under pre-storm winter conditions: (a) time series and (b) progressive vector run.

6. Comparisons between model results and field data

Selected comparisons are provided here to illustrate the broad agreement between the modelled and measured transport of buoyant Swan-Canning Estuary outflows.

From the analysis of samples collected during the August 1991 shelf-scale water quality survey (Cary *et al.* 1995) it was concluded that the Swan-Canning Estuary was the predominant generation area for the diatom *Skeletonema costatum*, and that the distribution of this diatom throughout the coastal waters indicated the scale of transport of water from the Swan-Canning system. On 16 August 1991, after preceding easterly to northerly winds, this diatom was found both in Cockburn Sound and also extending southward along the Sepia Depression (Figure 8b). The model predicted a similar behaviour for the buoyant Swan-Canning estuarine discharge under these wind conditions (Figure 8a).

Further support for the model simulations is drawn from the early work of Environmental Resources of Australia (1970), where pulses of buoyant Swan-Canning estuarine water (coloured brown by the planktonic riverine diatom *Melosira*) were tracked by aerial photography during winter 1970. Under easterly to northeasterly winds (see Figure 9a) the algae were observed to enter Cockburn Sound across the full width of its northern entrance, and also to round northern Garden Island and form a thin plume moving southward along Sepia Depression, as predicted by the model (Figures 5a and h). Under northerly to northwesterly winds (Figure 9b) the algae were found to move southward around Woodman Point and to proceed along the eastern side of the sound next to the mainland coast, as was also predicted by the model (Figures 5b and c).

The offshore propagation of buoyant estuarine discharge plumes under southeasterly winds and their northward propagation as coastally attached features under preceding southwesterly winds was inferred from satellite imagery on 23 August 1991 (Plate 1) during the SMCWS winter intensive survey. This plume behaviour under such winds was also predicted by the model (Figure 5e, f and g).

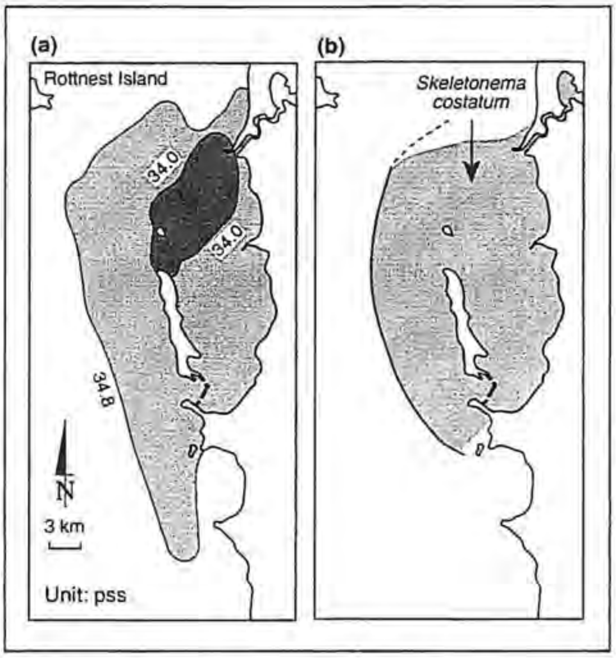

Figure 8. Comparison between (a) simulated surface salinity and (b) measured surface distribution of the estuarine diatom *Skeletonema costatum* (associated with the Swan-Canning estuarine plume) for 16 August 1991.

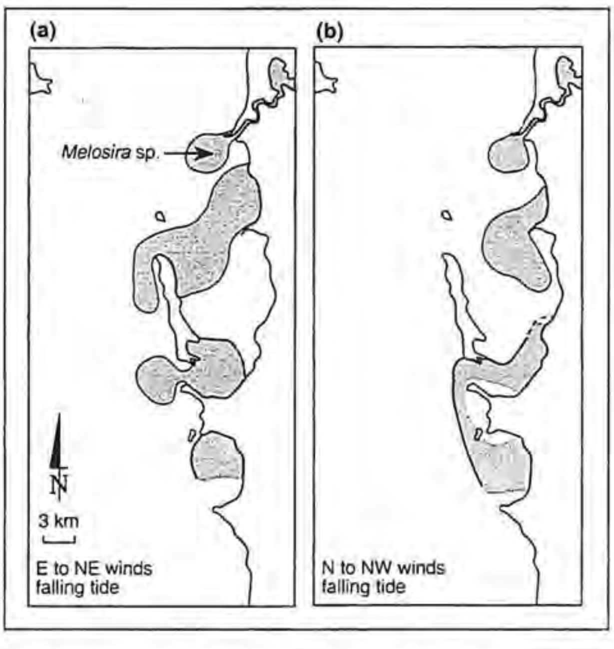

Figure 9. Observed positions of successive tidal pulses of Swan-Canning estuarine water (coloured brown by the estuarine diatom, *Melosira*) under (a) east-northeasterly winds and (b) north-northwesterly winds (from Environmental Resources of Australia, 1970).

Plate 1. The nearshore marine waters off metropolitan Perth showing buoyant plumes from the Swan-Canning and Peel-Harvey estuary outflows on 23 August, 1991 (darkest shading). Derived from Landsat Thematic Mapper colour image.

7. Investigation of the Peel-Harvey Estuary outflow into marine waters

7.1 Introduction

The Mandurah Channel was the sole ocean entrance to the Peel-Harvey estuarine system prior to the construction and opening of the Dawesville Channel, linking the Harvey Estuary to the sea in 1994. Prior to that time, the salinity of the Peel-Harvey estuarine system underwent a marked annual cycle, ranging from low values (< 10 pss) in winter to high values (35-45 pss) in summer (McComb *et al.* 1981; Hodgkin *et al.* 1985; D'Adamo and Lukatelich, 1985). This estuary discharged low density, buoyant water in winter and high density water in late summer, relative to the density of the receiving coastal waters. The behaviour of both buoyant and dense plumes has therefore been modelled. The modelling was confined to the situation before the construction of the Dawesville Channel, because it was under this situation that the SMCWS field data were collected.

7.2 Transport of the buoyant plume from Mandurah

The three-dimensional baroclinic model was used to simulate the transport of buoyant plumes from the Peel-Harvey estuary under several wind conditions and with an estuarine discharge based on a freshwater flow of 60 $m^3 s^{-1}$. Field studies (D'Adamo *et al.* 1995a, Mills *et al.* 1996) have shown that this plume can extend into Comet Bay, Warnbro Sound, Sepia Depression and offshore, under winds from the southerly quadrants.

For southwesterly winds the model predicted that the plume is confined against the coast and driven northward through Comet Bay, as shown by the simulated surface salinity fields at 0.5, 1 and 1.5 days (Figure 10). The plume extended along eastern Comet Bay in 0.5 days. It then crossed the reefs and shallows off Becher Point and moved into Sepia Depression and Warnbro Sound. After 1.5 days the plume had reached Penguin Island and plume water extended across much of the surface of Warnbro Sound. In Comet Bay the model predicted that the plume had an offshore width of 4-5 km and a depth of 8-10 m. The model results are in general agreement with observations of the plume trajectory under similar winds during the period 20-22 August, 1991, shown in Figure 11 and discussed further in D'Adamo *et al.* (1995a).

For southerly winds, the model predicted that the plume develops to the north and north-northwest, and separates from the shore line within 4 km of Mandurah (Figure 12a). The plume deepens as it approaches the shallows and reefs about Becher Point, to the north of Comet Bay, and is forced into Sepia Depression.

Under southeasterly winds the model predicted offshore transport of the buoyant plume (Figure 12b) as a surface feature mainly detached from the seabed, but with deepening occurring just upstream of the reef-lines. Satellite imagery (Plate 1) confirms the offshore extension of the buoyant Mandurah plume under southeasterly wind conditions.

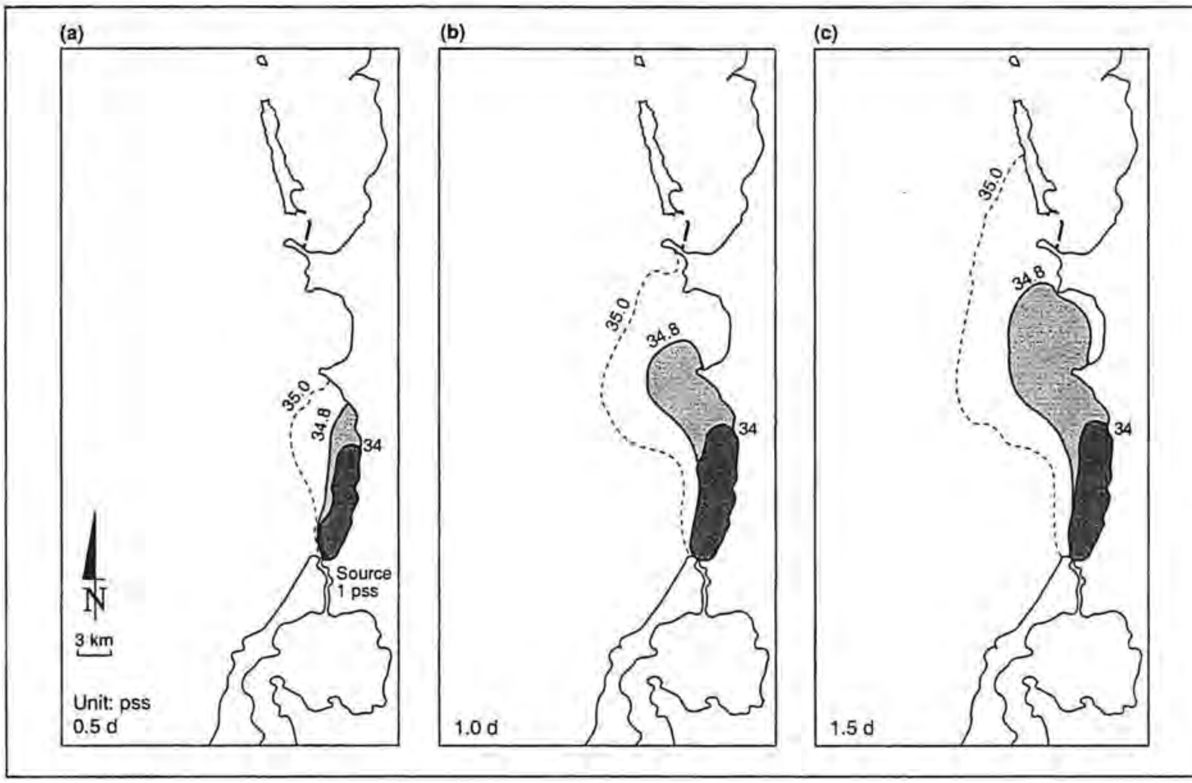

Figure 10. Baroclinically modelled surface salinity fields representing the transport of a buoyant Peel-Harvey estuarine plume under a southwesterly wind of 7.5 m s-1 after (a) 0.5 days (b) 1.0 day and (c) 1.5 days.

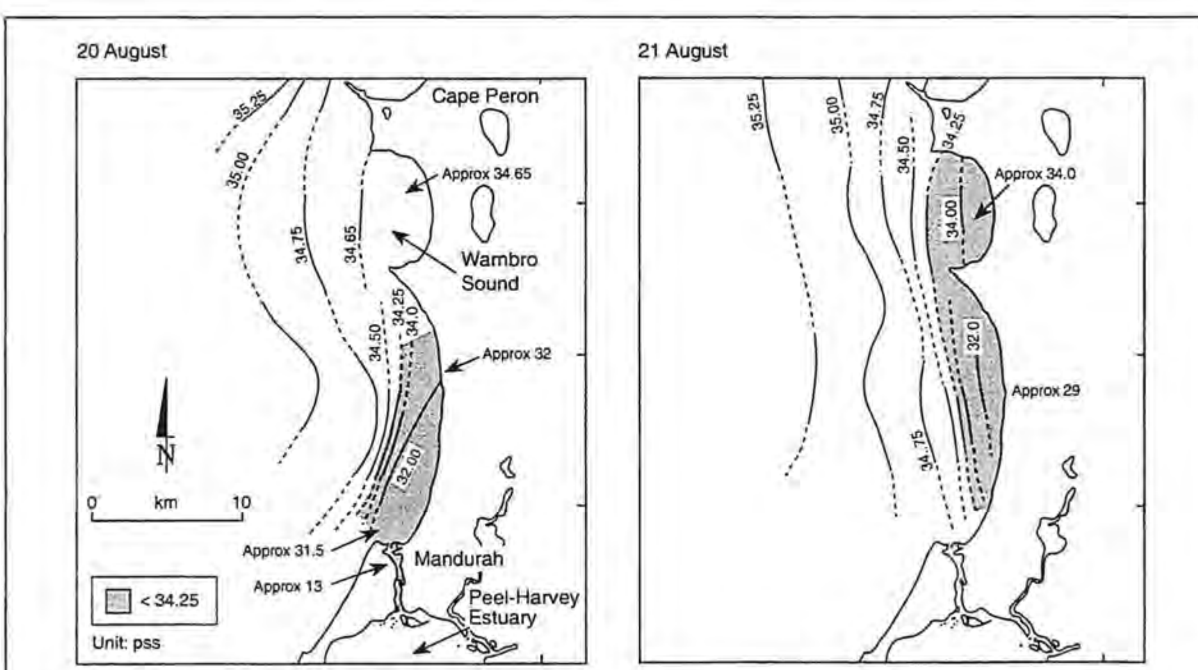

Figure 11. Surface salinity structure between Mandurah and Cape Peron on consecutive days in August 1991, showing the northward transport of buoyant Peel-Harvey outflow water under south-southwesterly winds.

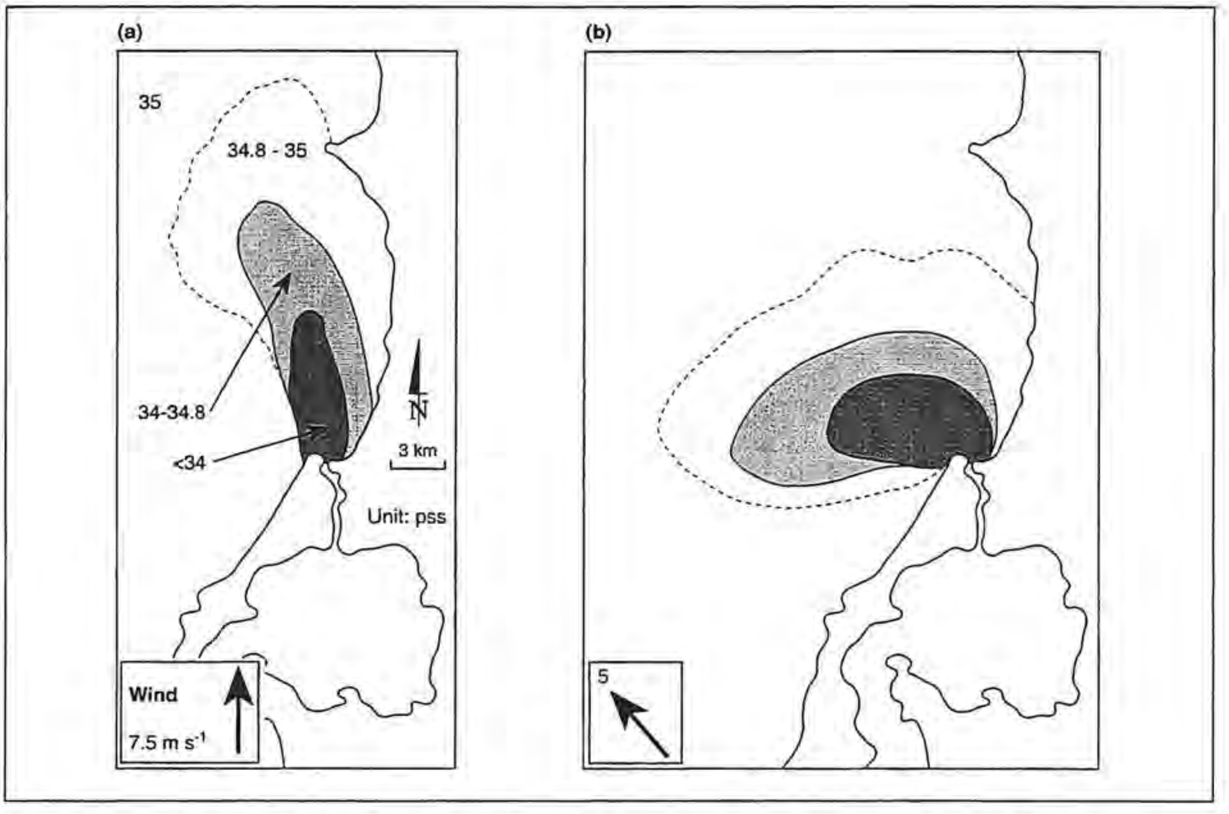

Figure 12. Baroclinically modelled surface salinity fields representing the transport of buoyant Peel-Harvey estuarine plumes after 0.75 days under (a) a southerly wind of 7.5 m s-1 and (b) a southeasterly wind of 5 m s-1.

7.3 Transport of the dense plume from Mandurah

The three-dimensional, baroclinic model was used to simulate the transport of a negatively buoyant plume originating from discharge of high salinity (40 pss) estuary water at Mandurah. Under summer conditions, the mean daily tidal exchange volume through the Mandurah Channel (before the construction of the Dawesville Channel) was estimated to be 5.5 x 10^6 m^3 (Hodgkin *et al.* 1985) which is equivalent to a daily average discharge rate of about 60 m^3 s^{-1}. The rate of estuarine discharge of dense water has been held constant in the model, however in reality, this discharge will occur as a series of ebb tidal pulses.

Under constant southeasterly wind (5 m s^{-1}) the model predicted that the hypersaline discharge mixes downwards and spreads across the sea bed as a negatively buoyant plume. The dense plume spreads about 3 km to the north and northwest, where it is constrained by the bathymetry of southern Comet Bay and the Murray Reefs. The plume then veers anticlockwise until it is obstructed by the coastline and is forced to flow southwestward. The dense plume was predicted to spread to the southwest as a coastally-attached plume, and to extend about 12 km southwest of Mandurah after 3.5 days (Figure 13). By contrast with the behaviour of the buoyant plume which tended to move well offshore under southeasterly winds, the dense plume remained nearshore when forced by the same wind.

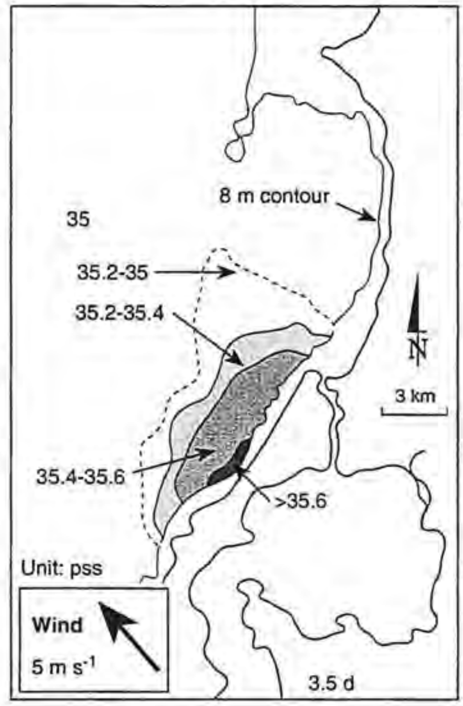

Figure 13. Baroclinically modelled surface salinity fields at 8 m depth representing the transport of a dense Peel-Harvey estuarine plume after 3.5 days under a southeasterly wind of 5 m s-1. The salinity of the source water was set at 40 pss.

There is some anecdotal evidence (from before the opening of the Dawesville Channel in 1994) to support this modelled behaviour. There have been observations from Falcon Bay, approximately 7 km southwest of the Mandurah Channel, of a southwestward moving plume of brown coloured water from Mandurah, hugging the coast. These observations were made on 2-3 occasions during mid-late summer under sustained light easterly wind conditions (M J Pannell, personal communication). Although there are no known field studies which can confirm the simulated behaviour of the dense plume, the anecdotal reports and the modelling results should be taken into account when designing future monitoring exercises.

8. Transport of water leaving the southern entrance of Cockburn Sound

During the winter runoff period the waters of Cockburn Sound are typically less saline and less dense than the surrounding shelf waters, due mainly to the incursion of low salinity plumes from the Swan-Canning Estuary under winds from the northerly quadrants (D'Adamo and Mills, 1995b; D'Adamo *et al.* 1995b) and the mixing of these plumes with the resident waters of the sound. Model results for this period indicate that easterly, northeasterly, northerly and northwesterly winds drive Cockburn Sound water out through the causeway bridge openings. Under these wind conditions, water exiting the southern entrance of Cockburn Sound in winter is driven southward as a buoyant plume past Shoalwater Bay and to the entrance of Warnbro Sound and Comet Bay. Figure 14 (from D'Adamo *et al.* 1995a) shows the results of a model simulation forced by southeasterly to northeasterly winds recorded on 13-15 August, 1991. After about 1.5 days, buoyant water from the southern entrance of Cockburn Sound had been transported to the

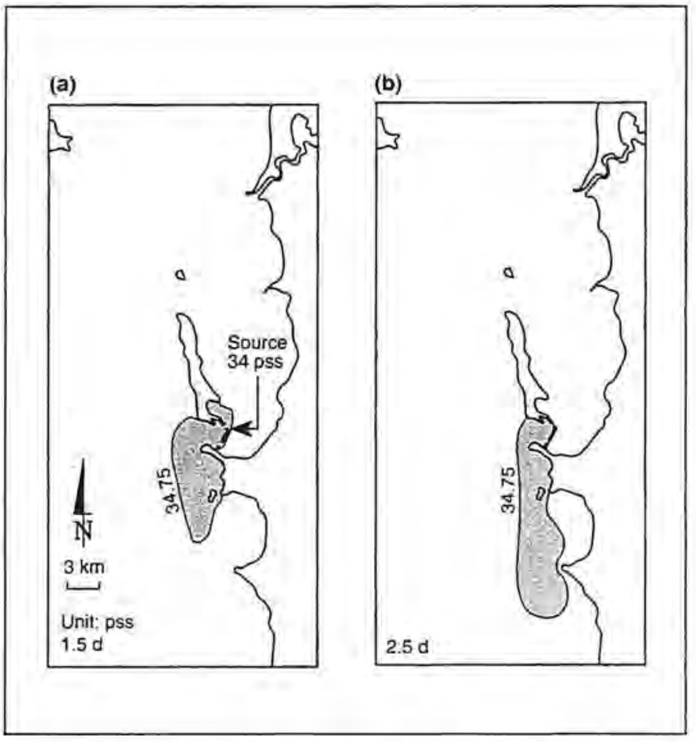

Figure 14. Baroclinically modelled surface salinity fields representing the southward transport of buoyant water out of the southern opening of Cockburn Sound under southeast to northeast winds (starting at 0000 hrs 13 August 1991) after (a) 1.5 days and (b) 2.5 days.

Warnbro Sound entrance, and after 2.5 days, the plume had entered Comet Bay. This is consistent with the conclusion from temperature-salinity survey data collected during this period (D'Adamo *et al.* 1995a) that low salinity water was transported from southern Cockburn Sound to Warnbro Sound under these conditions.

The model was also run under calm conditions (no wind) starting from an initial density distribution, derived from immediately post-storm measurements in winter, with Cockburn Sound water being vertically well-mixed, less saline and more buoyant relative to the surrounding waters (see Figure 8 of Mills and D'Adamo, 1995). This initial density structure is gravitationally unstable and, as shown by the simulated surface salinity contours (Figure 15), relatively buoyant Cockburn Sound water flows through the southern entrance into Sepia Depression and is then transported southward. Part of the buoyant plume subsequently enters Warnbro Sound.

9. Discussion

9.1 Swan-Canning Estuary outflow plume

Buoyant plumes discharged from the Swan-Canning Estuary are driven (under most wind conditions) to nearshore areas which tend to be both ecologically significant and sought after for multiple human uses. The plumes expose these nearshore areas to loads of nutrients, phytoplankton and various catchment-derived contaminants contained in the discharges, and this may result in adverse changes to the environment. Nitrogen loads from the catchments to the Swan-Canning Estuary have increased by more than 350 % since the 1960s (Deeley, in preparation). Maintenance of the environmental quality of Perth's coastal waters is therefore

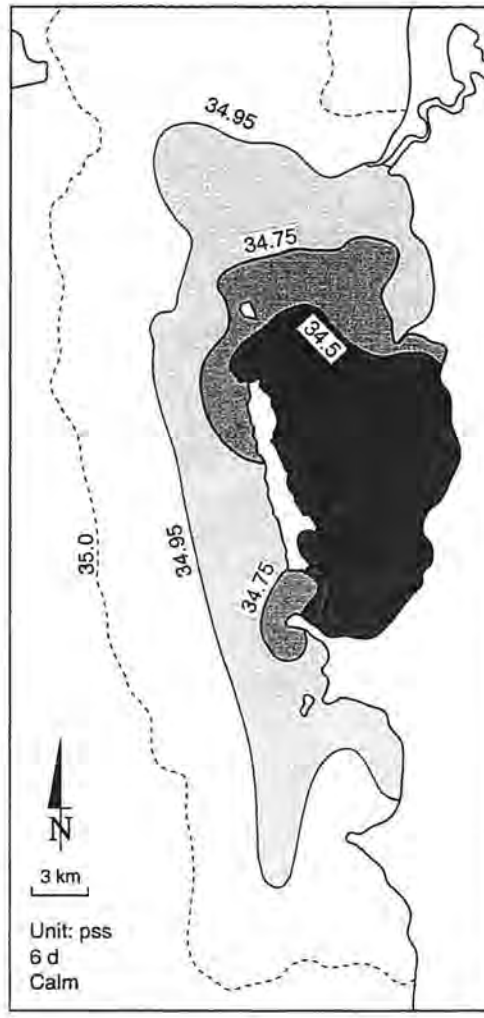

Figure 15. Baroclinically modelled surface salinity field representing buoyant outflow from Cockburn Sound after 6 days during calm 'winter' conditions.

inextricably linked to the management and control of nutrient and contaminant losses from the catchments and waterways of the Swan-Canning Estuary.

The wind drives buoyant surface plumes more rapidly than surrounding surface coastal waters. Within a few days, under favourable wind conditions, water from the Swan-Canning Estuary can reach much of the SMCWS area, including Gage Roads, Owen Anchorage, Cockburn Sound, Sepia Depression, Warnbro Sound and the area about Rottnest Island. This is consistent with the findings from the shelf-scale and local-scale water quality studies (Cary *et al.* 1995; D'Adamo *et al.* 1995a; Mills *et al.* 1996) that, in winter, estuarine outflows are a key factor in influencing water quality off much of metropolitan Perth. The spatial and temporal scales of transport of the Swan-Canning discharge should be taken into account in future environmental monitoring and management plans for Perth's coastal waters.

The plume modelling suggests that the eastern side of Success Bank and the northeastern margin of Owen Anchorage is exposed to nutrients discharged from the Swan-Canning Estuary under a wide range of wind conditions. This high nutrient exposure may explain the observed high biomass of epiphytes on seagrass leaves and the decline in the seagrass meadows of these areas.

The modelling confirms that under winds from the southwest quadrant the plume extends north of Fremantle next to the shore. The high incidence of the physiological deformity *imposex* in *Thais orbita* collected from the Cottesloe reefs (Field, 1993), an area where boating activity is low, the link between tributyltin contamination and this deformity, and the direction of the plume under the predominant southwest winds, together suggest that the tributyltin may be transported to these reefs from the mouth of the Swan-Canning Estuary and the inner port area.

Buoyant plumes tend to deepen and broaden as they approach submarine banks and reefs. The marine biological communities associated with these banks and reefs are therefore exposed to contaminants contained in the plume waters to depths even greater than the normal thickness of the plume.

Episodic winds from the northerly quadrants in winter drive low salinity water discharged from the Swan-Canning Estuary southward. As a result of these incursions of the estuarine plume into Cockburn Sound the salinity of the sound is lowered. This leads to a density difference between Cockburn Sound and the surrounding shelf waters which (as shown by the field data in D'Adamo *et al.* (1995b) and model results in Mills and D'Adamo (1995)) is one of the key determinants of the circulation and flushing regimes of the sound in winter. Further investigations of the winter flushing and exchange between Cockburn Sound and its surrounding waters need to take account of the influence of buoyancy inputs to the sound from the Swan-Canning Estuary.

9.2 Peel-Harvey Estuary outflow plume

The numerical simulations supported by field data and observations show that buoyant water discharged from the Peel-Harvey Estuary can be driven into Comet Bay, Warnbro Sound and Sepia Depression within 1-2 days under favourable wind conditions. The plume can also be driven off-shore, for example, under light to moderate southeasterly winds. Discharge from the Peel-Harvey Estuary contains significant loads of nutrients, phytoplankton and catchment-derived contaminants. Since the 1960s, nitrogen loads from rivers flowing into the Peel-Harvey Estuary have increased by 450 %, based on the estimates of Deeley *et al.* (in preparation). Shelf-scale water quality investigations identified outflow from the Peel-Harvey Estuary as a major determinant of water quality in winter (Cary *et al.* 1995) with widespread increases in nutrient levels up to 5-10 times background values being monitored. Hence catchment management plans designed to limit losses of nutrients and contaminants to the waterways should be motivated not only by the need to rehabilitate the Peel-Harvey estuary but also by the need to protect the environmental quality of Perth's southern metropolitan marine coastal waters.

The Shoalwater Islands Marine Park has been established in recognition of the high environmental and social value of this area. It has been shown that the Peel-Harvey Estuary plume can readily enter the marine park under southwesterly wind conditions which occur frequently throughout the year. Hence management of the environmental quality of the marine park must take into account the role of the Peel-Harvey Estuary plume (and other plumes from external sources) in contributing to the total loads of nutrients and other contaminants entering the marine park.

The behaviour of the Peel-Harvey Estuary plume depends on the density of the discharged water relative to oceanic water. During periods of strong river flow the plume occurs as a low salinity buoyant surface feature. At other times of the year the plume may have a similar density to surrounding coastal waters. In the late summer/autumn season of the years before 1994, prior to the opening of the Dawesville Channel, the estuary became strongly hypersaline and the plume mixed down and spread across the seabed, being strongly guided by the bathymetry. The potential for changes in plume behaviour arising from the modified annual cycle of salinity and density in the Peel-Harvey Estuary needs to be recognised in future monitoring of the plume and its effects on the marine environment. The dispersion patterns of nutrients and other contaminants discharged from the Dawesville Channel require further investigation.

9.3 Interconnectedness between Cockburn Sound and Warnboro Sound

Under favourable wind conditions, buoyant water can be driven out of the southern entrance of Cockburn Sound and, within 1-2 days, transported to Warnbro Sound and Comet Bay. This result further highlights the interconnectedness between the nearshore embayments. In particular, discharges from the southern entrance of Cockburn Sound are likely to periodically enter the Shoalwater Islands Marine Park. Hence the ongoing environmental monitoring of Cockburn Sound, the marine park, and other interconnected areas should be closely coordinated.

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Appendix 1

The values of the internal model parameter settings used in the simulations described in this paper are set out below. The role of these parameters within the context of the Princeton Ocean Model is fully described in Mellor (1993).

Internal model time step (s) =		180.0
External model time step (s) =		9.0
Number of time steps where external mode advective terms not updated =		5
Horizontal diffusivity Prandtl number =		1.0
Constant in time smoother to prevent solution splitting =		0.1
Constant in Smagorinsky horizontal viscosity =		0.1
Constant in Smagorinsky horizontal diffusivity		0.1
Initial vertical kinematic viscosity ($m^2 s^{-1}$) =		0.01
Initial vertical diffusivity ($m^2 s^{-1}$) =		0.0001
Initial horizontal kinematic viscosity ($m^2 s^{-1}$) =	10.0	
Initial horizontal diffusivity ($m^2 s^{-1}$) =		10.0
Bottom roughness parameter (m) =		0.002
Reference coriolis constant (s^{-1}) =		-7.7×10^{-5}
Beta ($m^{-1} s^{-1}$) =		0.0