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Three-dimensional hydrodynamic modelling of a coastal embayment for multiple use industrial discharge and infrastructure development

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Abstract:

Cockburn Sound is a coastal embayment located to the south of Fremantle on the Western Australian coast. The region is an important industrial centre, receiving numerous discharges to the Sound including those by Kwinana Power Station, BP Refinery, Tiwest Refinery and Water Corporation. In addition, the embayment supports multiple uses including commercial fishing, defence, recreation and provision of drinking water. Current and potential water quality issues facing the embayment include reduced circulation and sediment plumes arising from dredging and infrastructure development and thermal and saline plumes resulting from industrial discharges.

The Centre for Water Research at the University of Western Australia has conducted a series of detailed validations of the Estuary, Lake and Coastal Ocean Model (ELCOM), coupled with the Computation Aquatic Ecosystem Dynamics Model (CAEDYM) applied to Cockburn Sound. The high public profile of the site and the extent of the industrial use required extensive stakeholder interaction in the model construction and validation.

The validated and calibrated three-dimensional model has provided an integrated tool for numerous applications, across various spatial and temporal scales, including:

- The impact of the Perth Seawater Desalinisation Plant on stratification and dissolved oxygen dynamics in the Sound;
- The influence of harbour modifications in Jervoise Bay on flushing of the Australian Maritime Complex harbours;
- The impact of Fremantle Ports Kwinana Quays development on circulation within the Sound; and
- The impact of cooling water discharge from proposed High Efficiency Gas Turbines on thermal plumes.

This paper presents the extensive validation process of ELCOM in Cockburn Sound, and the application of this integrated tool to assess the impact of numerous interventions on varying spatial and temporal scales. Future modelling directions will also be discussed.

Keywords: *Cockburn Sound, hydrodynamic modelling, integrated tool, industrial development.*

1. INTRODUCTION

Cockburn Sound is a semi-enclosed coastal embayment located south of Perth along the Western Australian southern coast (Figure 1). The main basin is approximately 16 km long, 7 km wide, and has a maximum depth of 22 m. The surface area is approximately 80 km^2 and the volume approximately 1.2×10^9 m^3. Cockburn Sound is bounded to the east by the coastal mainland, to the west by Garden Island, and has a shallow ridge, approximately 10 m deep, that extends across its northern ocean boundary. At the southern end of the Sound, the mainland and Garden Island are connected by a solid rock-fill causeway, with two small openings to the sea that are approximately 300 and 600 m wide.

Over seasonal time-scales, the hydrodynamic behaviour of Cockburn Sound is dominated by surface wind stress and vertical density gradients (Yeates et al., 2007). Stratification is driven by a combination of salinity and temperature gradients that exist throughout the year (DEP, 1996; D'Adamo, 2002). During summer (November to March), strong south-westerly afternoon sea-breezes erode the weak stratification. In winter, the strength of the sea-breeze decreases and increased discharge from fresh groundwater springs along the eastern shoreline form a baroclinic flow which in combination, strengthen the stratification (D'Adamo, 2002).

Numerous thermal discharges are released into Cockburn Sound, with maximum flow rates of 10.16 m^3 s^{-1} and temperature differences between discharge and ambient waters of up to 12.7^oC. In addition, the Perth Seawater Desalination Plant releases a saline discharge into the Sound, at a flow rate of 2.3 m^{-3} s^1 and salinity 43% greater than ambient conditions. Figure 1 indicates the locations of current and proposed industrial discharges in the Sound, and proposed harbour developments.

2. METHODOLOGY

2.1. Estuary, Lake and Coastal Ocean Model

The Estuary, Lake and Coastal Ocean Model (ELCOM) is a three-dimensional hydrodynamics model designed to simulate the temporal and spatial variation in temperature and salinity in surface water bodies (Hodges et al., 2000). ELCOM solves the unsteady Reynolds-averaged Navier-Stokes equations using a semi-implicit method similar to the momentum solution in the TRIM code (Casulli and Cheng, 1992) with the addition of a quadratic Euler-Lagrange discretisation for scalar transport using a conservative flux-limited approach. Flow is solved using an Arakawa-C rectangular grid which has velocities defined on cell faces and the free-surface height and scalar concentrations defined at the cell centres. The free-surface height is solved by integrating the continuity equation for incompressible flow and is permitted to pass vertically through grid layers as required. Heat exchange at the surface is determined using standard bulk transfer models for nonpenetrative components of sensible heat transfer and evaporative heat loss that act on the surface cells only, long-wave radiation inputs and losses from the surface cells, and a penetrative flux due to shortwave radiation that heats the water column by following an exponential decay with depth that is given by Beer's Law. An explicit mixing model is applied to compute the vertical turbulent transport (Hodges et al., 2000).

ELCOM was configured according to the components in Table 1. The validated model configuration was adjusted to model scenarios described in proceeding sections.

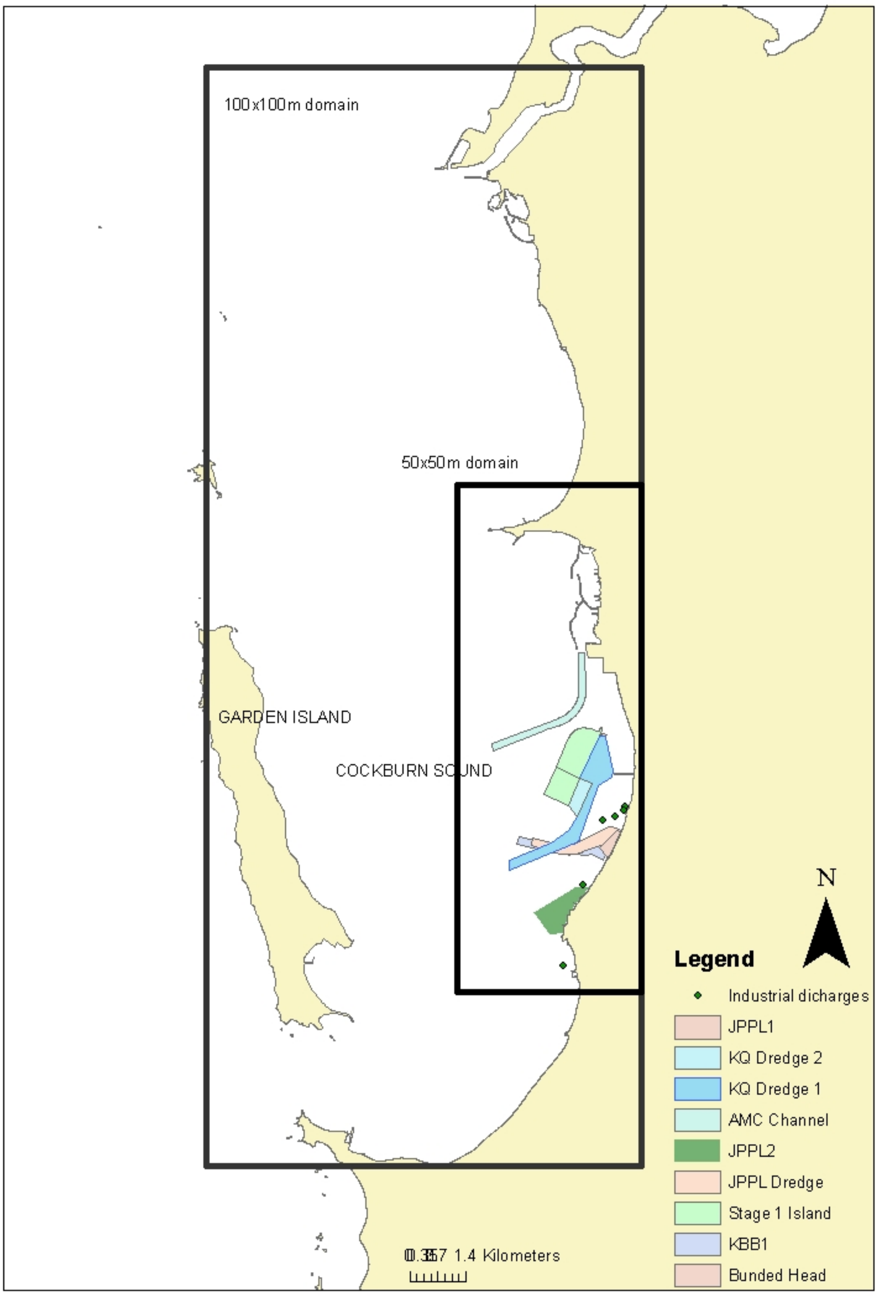

Figure 1. Map of Cockburn Sound, indicating proposed and current industrial discharges, and proposed harbour development. The outlined areas indicate the extent of the two modelling domains.

Table 1. Components of Cockburn Sound validation (temperature and salinity (T/S) and velocity (U/V)) simulations.

Component	**Validation T/S**	**Validation U/V**
Start time	23 Feb 2005 (year-long validation) 13 Dec 2006 (desalination in operation)	9 May 2006 (winter) 31 Jan 2006 (summer)
Period	400 days	62 days
Initial conditions	Velocity: zero Salinity: measured profile Temperature: measured profile	Velocity: zero Salinity: constant Temperature: measured profile
Time-step	90 seconds	60 seconds
Bathymetry	Horizontal: plaid grid 100x100m near power station and desalination outfalls, expanding to 200x200m. Vertical: 0.5-1m	Horizontal: plaid grid 100x100m for basin (Woodman Point to James Point), 200x100m extending 10km north of Fremantle Port. Vertical: 1m
Meteorological Data	BOM Swanbourne and Perth airport (10 min). Solar radiation: Caversham (10 min)	Winter: BOM Garden Island (10 min). Summer: in situ LDS (15 min). Solar radiation: Caversham (10 min)
Boundary conditions	Water Heights: FP Fremantle Fishing Harbour Station- 15 min. Water T/S: vertically averaged measurements taken in 2005/2006.	Water heights: FP Fremantle Fishing Harbour Station- 15 min. Water T/S: vertically averaged measurements taken in 2005/2006.

2.2. Observation Data

To enable validation of the model, water column temperature, salinity and velocity data were sourced. Water column temperature and salinity for Cockburn Sound were sourced by Oceanica Consulting Pty Ltd. The data included profile measurements at four locations throughout the Sound on nine occasions during 2005. Weekly profiles at the same locations for the summer months (Dec- Mar) were available from the Cockburn Sound Management Council. Intensive profiling was undertaken by the Centre For Water Research during week-long field campaigns in Dec 2006 and Apr 2007.

Validation of the velocities in Cockburn Sound focussed on ADCP deployments at two locations: the old spoil grounds site (“FSG”) and the northern basin site (“FNB”), during a summer and winter period (31 January - March 10 2007 and 9 May – 10 July 2006). The FSG site is located on the eastern shelf of the Sound and has a depth of 6.5m, while the FNB site is located in a more complex topographic environment, approximately 500 meters west of the eastern shelf of the Sound that sees the water depth drop rapidly from 10 to 20 meters.

3. RESULTS AND DISCUSSION

3.1. Model Validation

The temperature and salinity validation showed an excellent comparison between measured and modelled values. For example, Figure 2 presents a transect of measured and simulated salinity along the main shipping channel in Cockburn Sound in the morning of 27 April 2007. The field data shows a lens with elevated salinity at the bottom of the channel associated with the saline discharge from the Perth Seawater Desalination Plant. The simulation results show the model has captured the intensity and extent of this feature. At all sampling locations, the correlation coefficients for temperature and salinity ranged from 0.94 - 0.99 and 0.84 – 0.94 respectively.

The velocity validation utilised contour plot comparisons (to display the temporal and vertical variability) and histogram comparisons (an integrative summary of the model performance at each depth) of current speed and direction over the full depth at both stations. Figure 3 presents current velocity and direction at the FSG site between 19 March and 25 March 2007. At the FSG site in summer, the field data show the currents are generally unidirectional over depth, with velocities slightly slower at depth due to bottom friction. Current direction is strongly related to the wind direction, with the predominant currents in summer to the north. At the FNB site (not shown), velocities are far more complex, with numerous examples of three-layer flow operating despite the relatively well-mixed conditions. The simulation results reflect the current patterns in both summer and winter periods, and in two topographically different locations within the Sound. Root mean squared error values ranged from 0.019 m s^{-1} to 0.047 m s^{-1} and mean absolute error values ranged from 0.015 m s^{-1} to 0.037 m s^{-1}, indicating the model is fit for purpose for scenario modelling.

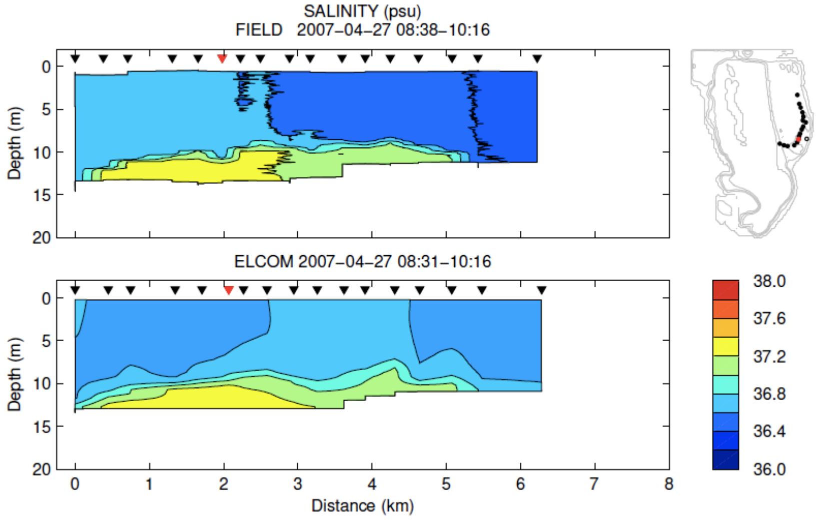

Figure 2. Transect of measured (upper panel) and simulated (lower panel) salinity along the main shipping channel in Cockburn Sound in the morning of 27 April 2007. Source: Okely et al., 2007.

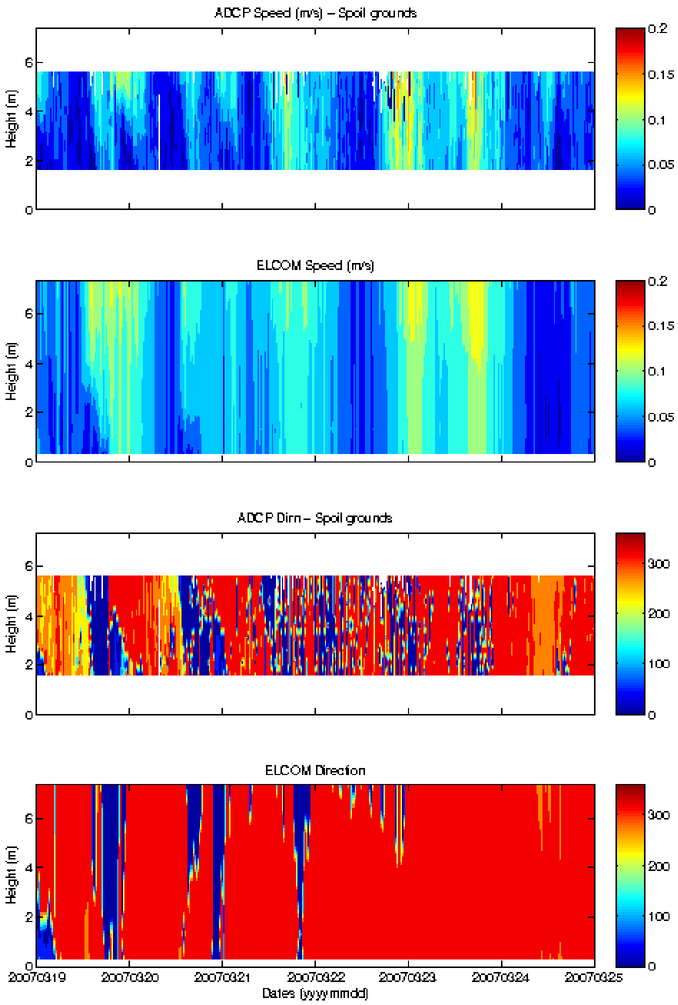

Figure 3. Measured (ADCP) speed, simulated (ELCOM) speed, measured direction and simulated direction for six days at the Spoil grounds location for 19 Mar – 25 Mar 2007. Source: Antenucci et al., 2008.

3.2. Perth Desalination Discharge

The Perth Seawater Desalination Plant (PSDP) obtains water from the Sound at a location approximately 160 metres from the coastline, and discharges the waste brine via a 40 port diffuser approximately 300 metres from the coast. Detailed field investigations were carried out in 2006 and 2007 to determine the near and far-field mixing of the saline plume generated by the plant, and to provide validation data for the modelling.

A key factor in the environmental approvals process was the accurate representation of the horizontal scale of the saline plume. Simulation results averaged over an annual cycle (Figure 4) show the average density difference induced by the discharge. The plume is generally confined to the shallow eastern margin of the sound, where it tends to reside in the dredged shipping channels until being vertical mixed by wind events. The maximum density difference observed was 1 kg m $^{-3}$, equivalent to a salinity difference of approximately 0.75 PSU. The shape of the plume to the north and south follows the dredged shipping channels, as the plume moves under gravity to these deeper locations. The transect in Figure 2 intersected the saline plume in the main shipping channel. Dissolved oxygen conditions under the stratification did not draw down to low levels, as the stratification is periodically broken down by wind mixing and oxygen is therefore replenished.

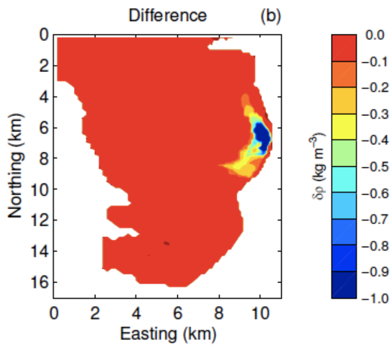

Figure 4. Average density difference between the base case and desalination discharge. Source: Yeates et al., 2006.

3.3. Jervoise Harbour Modifications

A study is currently being undertaken to determine the flushing times for each of the months December 2006 to March 2007 of the northern and southern harbours in the AMC complex of Jervoise Bay. The velocity validation configuration was modified to assess the impact of several small modifications to the harbour breakwater on flushing times. The 100x100m horizontal resolution bathymetric data was interpolated to 50x50m over the Sound, down to 20x20m over the harbours. The overall domain was cut down to cover only the eastern shelf including Jervoise Bay, to keep run times reasonable with the increased model resolution. Spatially and depth-averaged flushing times were determined for each of the harbours. Flushing times were also determined for a series of profile points throughout each of the harbours to gain some insight in to spatial variability, of which there was some noted in the northern harbour in particular. Preliminary results suggest that the inclusion of a 100m gap down to 2m below mean sea level in the southern breakwater of the northern harbour provides a significant reduction in the flushing time, with associated water quality benefits.

3.4. Kwinana Quays Offshore Development

Due to increasing industrial pressure on Fremantle Harbour, Fremantle Ports are currently planning the development of a harbour (Kwinana Quays) in Cockburn Sound. Extensive dredging and reclamation operations will be involved in the construction of the harbour. There are a number of issues to be addressed in the environmental approvals process in relation to this development including the fate of nearby thermal and saline plumes, the impact on circulation of the Sound, the impact on residence time in the AMC Harbours and the ability of works to meet their assigned Low Ecological Protection Area (LEPA) management areas with respect to temperature and salinity. The validated ELCOM model has been applied to simulate a number of scenarios to assess the impact of the development, during each stage of its construction. The model configuration has been extended to cover a full one-year period during the construction of the harbours. A nested grid set up was utilised where water height, temperature and salinity of the 100x100m plaid grid was provided as open boundary conditions to the

50x50m inner model grid. The velocity fields produced by the model have also been exported for use by a third-party (APASA Pty Ltd) in the simulation of dredge plumes associated with the construction.

4. CONCLUSIONS

A key outcome of this work has been the acceptance of the model performance by both the regulatory agencies and the industries concerned. This has been achieved in less than a two-year timeframe via a heavy reliance on targeted field campaigns for model validation, which have greatly increased confidence in the predictions. The model has now followed a development path whereby each new project builds on existing work, as each of the industries sees the cost effectiveness of this "open" resource approach, both in terms of reduced effort in re-establishing a model from scratch, but more importantly as it has simplified the environmental approvals process.

The reasons for the success of the model can also be traced to the flexibility of the model in its application to problems of varying spatial and temporal scales. The baroclinic nature of the model and its ability to accurately handle stratification and vertical mixing has been a critical factor, due to the buoyancy sources from the desalination and thermal plant discharges.

Future uses of the validated model include modelling of proposed industrial discharges into the Sound, for example, thermal plume modelling of cooling water discharge from proposed High Efficiency Gas Turbines. In addition, the Computation Aquatic Ecosystem Dynamics Model (CAEDYM) has been coupled with ELCOM to model dissolved oxygen, nutrients, phytoplankton and seagrasses, in association with the hydrodynamics of the Sound (Okely et al., 2006). This will continue to provide industries and the community with an integrated tool to assess the impact of developments on the Sound, and enable management of this heavily utilised area.

5. ACKNOWLEDGEMENTS

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