PEER REVIEW OF STUDIES FOR DESALINATION PLANT DISCHARGE, COCKBURN SOUND

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Summary

This document is primarily a review of the assessment by van Senden and Miller (2005) of the potential impact of discharge from a desalination plant on dissolved oxygen levels in Cockburn Sound. Van Senden and Miller's study is based on a set of simple models that are not adequately justified or tested against data. Their conclusions are not well supported by their analysis, and their study leaves a high degree of uncertainty about the likely impact of the discharge.

Background (supplied by WA DoE)

The Water Corporation of Western Australia proposes to discharge hypersaline return water (180 Ml/d) from a desalination plant to Cockburn Sound. The Water Corporation has commissioned a report detailing technical studies to assess any change in stratification and dissolved oxygen regimes in the deep basin of Cockburn Sound as a result of return water discharge, and any associated biogeochemical or ecological effects and their significance.

The EPA Services Unit is seeking a technical appraisal and peer review of the above studies.

Scope of Work (supplied by WA DoE)

Peer review the technical studies, giving particular attention to:

- the inclusion and treatment of relevant hydrodynamic, biogeochemical and ecological processes;
- the adequacy of environmental characterisation and key parameter estimation for the purposes of these studies;
- the appropriateness of investigation design, assumptions used and application of methods, including validation;
- the interpretation of results, and whether the conclusions are justified by the material presented in the report, and
- the level of confidence/uncertainty that can be placed on the conclusions, including the ecological change predicted

Reports reviewed

Principal report:
van Senden and Miller (2005): Stratification and dissolved oxygen issues in Cockburn Sound pertaining to discharge of brine from desalination. University of New South Wales, Water Research Laboratory Technical Report, March 2005

Supporting reports:
D'Adamo (2002): Exchange and mixing in Cockburn Sound, Western Australia: a seasonally stratified, micro-tidal, semi-enclosed coastal embayment. PhD thesis, Canterbury University, NZ.
Lord (2005): Ecological assessment of the effects of discharge of seawater concentrate from the Perth seawater desalination plant on Cockburn Sound. D.A. Lord and Associates Report 05/028/1, March 2005.
Pattiaratchi (2005): A pilot field measurement program to define dissolved oxygen dynamics in Cockburn Sound. Centre for Water Research UWA, February 2005.
Read and Oldham (2005): Sediment oxygen demand in the Cockburn Sound deep basin. Centre for Water Research UWA, 9 March 2005.
Worley (2204): Perth desalination plant: modelling of proposed subsea discharge into Cockburn Sound. Worley Pty Ltd Report 302/05563/A13, 27 Sept 2005.
Worley (2005): Perth desalination plant stratification and dissolved oxygen issues. Worley Pty Ltd Report 302/05563/A12, 11 March 2005.

Ecology of the Sound

From the observed data presented in the reports, it is clear that Cockburn Sound (particularly the Southern Deep basin) is already under considerable ecological pressure with low bottom water dissolved oxygen and elevated sediment organic and metal content, due to historical industrial activities in the region. Observations as low as 25% saturation (~2mg/l) are reported for 28-29 April 1994 in Masini (1995) (quoted in van Senden and Miller, 2005 – p16 and fig. 3.5). Lord (2005) goes on to quote "any change in the hydrodynamic regime which restricts oxygen replenishment of deep basin waters (e.g. increased vertical stratification) will increase the likelihood of sediment anoxia events". All reports agree that calm periods in autumn pose the most risk for low bottom water oxygen; however, few data are available and these demonstrate significant spatial heterogeneity. As the most recent data for this period is from a study completed 11 years ago there is considerable uncertainty in the conditions currently prevailing in the deep water throughout the Sound.

There is conflict of opinion as to whether the sediments are predisposed to efflux of nutrients and metals under low (< 2mg/l) DO concentrations. Read & Oldham (2005) note "that as the sediment in Cockburn Sound is predominantly carbonate sand, anoxia is unlikely to result in the release of nutrients and metals." This is based on the assumption that the sediments are low in iron hydrous oxides and qualified by the need for further observations to be made. Lord (2005) believes that there is a "greater concentration of organics and fine sediments and industrial contaminants found in the deeper basins of the

Sound" and that diversity of benthic invertebrate fauna "was generally inversely correlated with heavy metal concentrations (eg lead and nickel)". Both studies agree that there is a paucity of relevant local data to ascertain the likely biogeochemical impacts of the proposed brine discharges into the Sound.

Conceptual model in the van Senden and Miller report

Van Senden and Miller (2005) assume the following conceptual model for the brine discharge from the desalination plant. The brine will have a flow-rate of 180 Ml/day, elevated by 26 psu in salinity, and 1-2° in temperature, above ambient. It will be released through a diffuser on the eastern shelf of Cockburn Sound in approximately 10 m of water. It is expected to flow in a dense plume, under the influence of gravity, down the Calista Shipping Channel, and into the deep (20 m) basin of Cockburn Sound. In flowing down the Calista Channel, it may be diluted to ambient density. Alternatively, it may form a dense brine layer in the bottom of the Sound. This layer will be subject to mixing and entrainment of oxygenated surface water by winds. It will also be deoxygenated by bacteria and other organisms in the sediment. If insufficiently mixed from above, the dense brine layer may become anoxic, with potentially serious ecological consequences for the Sound.

Quantitative models

The following quantitative models are introduced in the reports:

Diffuser: Worley (2004) describes a conceptual diffuser configuration aimed to achieve a dilution of 45, thereby reducing the discharged salinity from 62 to 37.

Intermediate mixing: Worley (2004) describes implementation of the 3-d hydrodynamic model *EFDC* for Cockburn Sound. Van Senden and Miller (2005) use results from this model to infer plume behaviour between the diffuser and the deep Cockburn Sound basin.

Gravity current: van Senden and Miller (2005) adapt a 2-d, analytic, gravity current model (due to Bonnecaze and Lister) to describe the flow and mixing of the saline plume down the Calista Channel to the deep basin.

Vertical-mixing model: Following D'Adamo (2002), van Senden and Miller (2005) use the 1-d mixed-layer model of Pollard, Rhines and Thompson to describe wind-driven erosion of the deep saline layer.

Sediment-oxygen-demand model: Sediment oxygen demand and, thus, oxygen removal from the deep dense layer, is modelled empirically as proportional to the oxygen concentration.

Box model: The deep basin of Cockburn Sound is modelled as a single (horizontally homogeneous) box containing 3 layers, increasing in salinity with depth. The deepest layer is the brine released from the desalination plant. The salinity assumed for this deep layer is best described as "an educated guess" based on a combination of the diffuser, EFDC and gravity-current models. Dilutions (from the discharge point to the deep basin) of 60, 90 and 120 were adopted. Processes occurring in the box are:

- vertical mixing and entrainment of oxygenated surface water, driven by surface winds, and described by the vertical-mixing model;
- oxygen consumption in the water-column, described by an exponential, with a 7% per day loss, and a diurnal variation of 2.4% amplitude representing respiration and photosynthesis;
- oxygen consumption in the deep layer, described by the sediment-oxygen-demand model;
- flushing to the open ocean, with a flushing time of 47 days - it was unclear from the description in the report how this was implemented.

Comment on the quantitative models

This section assesses the implications of the models and their assumptions for the conclusions of the report. Technical comment on the physical models is included in the Appendix.

The EFDC model (Worley, 2004) appears to be a state-of-the-art hydrodynamic model. This model is used (van Senden and Miller, 2005) to assist with initial plume-dilution estimates, but it is not used to address the detailed dynamics of the deep brine layer, including processes such as mixing and ventilation which are critical to the conclusions. Comparisons of EFDC results with data are acknowledged to be poor (Worley, 2004).

The other models used by van Senden and Miller, for gravity-current flow, vertical mixing and sediment-oxygen demand, are all conceptually and mathematically simple. For the gravity-current and vertical-mixing models, the underlying assumptions are not discussed in detail and, more seriously, the models are not justified at all against existing data in the reports.

Van Senden and Miller's estimate of the salinity in the deep basin is based on the diffuser, EFDC and gravity-current models. Detailed design for the diffuser is yet to occur. If we take the design-dilution of 45 at face value, further dilution to the assumed values of between 60 and 120 requires a factor of only about 1.5 to 3 in the cascade from the diffuser to the deep basin. However, van Senden and Miller's consideration of the EFDC and gravity-current models gives no cause for confidence that they have the dynamics or the parameter values (in particular, the entrainment coefficient in the gravity current model) correct. At the very least, given that the two models are independent, their representation of the dense plume could have been compared. Cockburn Sound is hypersaline in the summer and autumn, and the models could have been tested against its known salinity dynamics.

The gravity current model has no time variation, and the EFDC model appears to have been run only under idealised conditions. Two potentially deleterious scenarios, not covered by the modelling, come to mind. Under calm conditions, and under the influence of the earth's rotation, the dense effluent may pool around the diffuser. Secondly, rather than spreading evenly through the Sound, the dense plume may turn left at the foot of the slope, again under the influence of the earth's rotation, and head for Mangles Bay.

The box-model for pelagic oxygen (van Senden & Miller, 2005) is very simple in its representation of water-column dissolved-oxygen dynamics. The model is poorly described and appears to neglect diffusive fluxes at the air-sea interface and between layers. Detail relating to oxygen concentration following entrainment of water from adjacent layers is omitted and the modelled evolution of dissolved oxygen concentrations throughout the water column is unclear.

The box model invokes subsidiary models for vertical-mixing and sediment-oxygen demand. The former, used to describe the mixing of both oxygen and salt, is well established for deep-ocean application, but represents a dramatically simplified description of turbulent processes. Its use should have been justified by comparison with Cockburn Sound data. By contrast, the sediment-oxygen-demand model is entirely based on data, but appears to be a poor match to laboratory results and, when incorporated within the box model, does not reproduce the available field data (such as the 2 mg/l oxygen concentrations noted above).

Fundamentally, the hypothesis central to the modelling rationale is that deep-water dissolved-oxygen concentrations are directly controlled by wind-induced mixing events: however, this is not supported by the observations (their figures 3.4 and 3.5). The box model is unproven and without validation against observations. There has been no assessment or justification of its suitability to simulate dissolved-oxygen concentrations in the Sound. The data for modelled and observed bottom-water dissolved oxygen in the report indicate that the model consistently fails to reproduce the low concentrations observed in the southern basin, even under the 'worst case scenario'.

As the model appears unable to simulate existing conditions in the Sound, one can have little confidence in its ability to predict changed conditions under the various scenarios presented. Accordingly, these scenario results do not provide an adequate basis for evaluation of the environmental impact of the proposed brine discharge.

Further, van Senden and Miller (2005) claim in their *Executive Summary* that their models of the Sound can be considered "robust". Robustness implies that conclusions from the modelling are not sensitive to assumptions in the models. It is a most important characteristic when there are doubts about the applicability or accuracy of the models. We do not consider that the modelling in this report has been demonstrated to be robust.

Concluding comment

The set of reports paints a picture of a Sound already under ecological stress. The simple models employed by van Senden and Miller (2005) may not be wrong, but can have no credence until they are properly tested – against data, and against more sophisticated models. Even if their conclusions were to be believed, their report seems to provide only marginal reassurance that the desalination plant would not worsen environmental conditions in the Sound. For example, a decrease in bottom water DO of 0.5 mg/l (which appears to be typical of the impact of saline discharge predicted by the box model – Figures 4.4 and 4.5 and Tables 4.1 and 4.2) may be significant if subtracted from the 2 mg/l in situ concentrations actually observed in the past.

In general, the assessments in the reports fail to convey the seriousness and reality of a regime shift to an anoxic eutrophic embayment with sediment efflux of ammonium, sustained algal blooms (possibly of nuisance algae), sediment hypoxia, reduced benthic diversity, hydrogen sulphide production and associated bacterial mats. Given past observations of hypoxic events in bottom waters in Cockburn Sound, there would appear to be a possibility of these events and insufficient evidence is provided to state that beyond reasonable doubt the brine discharge will have no significant environmental impact.

Ideally, the environmental study should be repeated and strengthened. If the desalination plant is to proceed, and the outfall is to be placed in Cockburn Sound as described in these reports, then we endorse the recommendation in the final sentence of van Senden and Miller's *Executive Summary*: that an environmental management regime be established for the plant, to include monitoring, trigger values, and contingency plans. An operational model of the physics and biogeochemistry could be incorporated into such a management system.

Appendix – more detailed comment on physical models

EFDC

From the description provided in Worley (2004), EFDC appears to be a standard, state-of-the-art hydrodynamic model. It features second-order turbulence closure (see below). Worley (2004) provides comparison of the model performance with current meter records. This is not a good test of the model and, not surprisingly, produces poor results. To give confidence in its performance, the model should be assessed against 3-d scalar fields such as salinity.

The model was really only run for demonstration purposes. After 25 days of simulation with the saline discharge, salinity in the Sound was still rising.

Worley (2005) provide qualitative tests of the model prediction for existing plumes in Cockburn Sound. Unlike the desalination-plant plume, these are positively buoyant. The comparisons cannot be considered as a good test of the negatively buoyant plume.

Van Senden and Miller (2005) used the model runs to assess the behaviour of the dense plume between the discharge point and the deep basin. No model results are actually shown in their report, nor is there quantitative assessment of the model behaviour.

As noted above, because Cockburn Sound is already hypersaline for parts of the year, its present state (i.e. before the saline discharge is introduced) should consitute a good test of the model's ability to handle high-salinity dynamics.

Bonnecaze and Lister gravity current model

This is a very simple model of a density current. It ignores three-dimensionality, time-variability, the earth's rotation, variations in bathymetry, and so on. Turbulence is parameterised by an entrainment coefficient, the magnitude of which critically affects the results. The model was developed (by Bonnecaze and Lister) to describe a dense plume of suspended particles. The implementation by van Senden and Miller refers to "salt particles". Much of the time, the plume will probably appear more as a "river" down the slope, without the "nose" depicted in their diagram. Use of this model is an interesting theoretical exercise, but the assumptions appear to be too severe to justify adoption of its predictions.

Pollard-Rhines-Thompson (PRT) mixing model

PRT is a one-dimensional (vertical) wind-mixing model, dating from 1973, and originally developed for the open-ocean mixed layer. Van Senden and Miller justify its use by reference to D'Adamo (2002). The D'Adamo analysis is based on lake concepts, and appears to be formally inapplicable to Cockburn Sound, because it does not account for the earth's rotation. (The internal seiching period, for example, is estimated in D'Adamo's Appendix C as 40 hours, longer than the inertial period of about 25 hours). D'Adamo assumes the PRT formulation to be valid for internal seiching, which cannot occur at periods longer than the inertial period. This does not necessarily invalidate the PRT formulae. However, despite the claim by van Senden and Miller that "use of the formulae is verified against data by D'Adamo (2002)", we could find no such validation. It is much more standard, in coastal waters, to use mixing rates based on 2nd-order closure-schemes like Mellor-Yamada or κ-ε. EFDC uses Mellor-Yamada. These schemes can be implemented quite simply in one dimension, but again would need thorough testing against data.

Box model
As noted above, the physics of the box model is inadequately described by van Senden and Miller (2005). This is particularly true of its representation of oxygen mixing and flushing. We have described above our (serious) concerns with the mixing and sediment-oxygen-demand sub-models. Most seriously, the fundamental assumption of the model, that wind stress controls deep oxygen levels, appears unsupported by existing data.

However, it is likely, as claimed in the report, that periods of calm weather will be critical. D'Adamo (2002) suggests periods of up to 25 days when mixing will not reach the bottom in the deep basin (p215). Van Senden and Miller note calm periods (defined by winds consistently below 7 m/s) of up to 14 days. We have raised the possibility that effluent may pool near the diffuser under low winds.