Linking Near and Far Field Hydrodynamic Models for Simulation of Desalination Plant Brine Discharges

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Abstract
A desalination plant is proposed to be the major water supply to the Olympic Dam Expansion Mining project. Located in the Upper Spencer Gulf, South Australia, the site was chosen due to the existence of strong currents and their likely advantages in terms of mixing and dilution of discharged return water. A high-resolution hydrodynamic model (ELCOM) was constructed and, through a rigorous review process, was shown to reproduce the intricate details of the Spencer Gulf dynamics, including those characterising the discharge site. Notwithstanding this, it was found that deploying typically adopted 'direct insertion' techniques to simulate the brine discharge within the hydrodynamic model were problematic. Specifically, it was found that direct insertion techniques delivered highly conservative brine dilution predictions in and around the proposed site, and that these were grid and timestep dependent. To improve the predictive capability, a strategy to link validated Computational Fluid Dynamics (CFD) predictions to hydrodynamic simulations was devised. In this strategy, environmental conditions from ELCOM were used to produce boundary conditions for execution of a suite of CFD simulations. In turn, the CFD simulations provided the brine dilutions and flow rates to be applied in ELCOM. In order to conserve mass in a system-wide sense, artificial salt sinks were introduced to the ELCOM model such that salt quantities were conserved. As a result of this process, ELCOM predictions were naturally very similar to CFD predictions near the diffuser, whilst at the same time they produced an area of influence (further afield) comparable to direct insertion methods. It was concluded that the linkage of the models, in comparison to direct insertion methods, constituted a more realistic and defensible alternative to predict the far-field dispersion of outfall discharges, particularly with regards to the estimation of return water dilution in the immediate vicinity of an outfall location.

Keywords
Desalination; outfall discharges; hydrodynamic modelling; brine discharge, Spencer Gulf.

INTRODUCTION

Desalination plants are increasingly becoming one of the key elements of securing public and industrial water supply. In Australia, all major urban centres in the Australian continent (except Darwin) have desalination plants either in operation (Perth, Brisbane, and Sydney) or under construction (Adelaide, Melbourne, and another in Perth). In addition to the major capital city plants, a desalination plant to be located at Port Bonython, South Australia (Figure 1), is being considered as the major water supply to the Olympic Dam Expansion Mining project, located near Roxby Downs, which is about 320 km inland from the site. The project requires 280 ML/day of water at peak production rates, which translates to 650 ML/day extraction and 370 ML/day desalination plant discharge (DPD). Port Bonython was chosen due to the existence of an approximate 25 m deep channel in a constriction known as "The Rip" (i.e. between Point Lowly and Ward Spit), in which water velocities can reach up to 1.5 m/s, and therefore would likely promote good conditions in terms of mixing and dilution of the discharge.

The proposed DPD would discharge to an area within the Upper Spencer Gulf Marine Park, where some sensitive marine receptors exist. These receptors include spawning grounds from the giant cuttlefish, and endemic seagrass, reefs and sponge gardens species (Figure 1). Occurrences of protected species such as the Great White Shark are also common in the area.

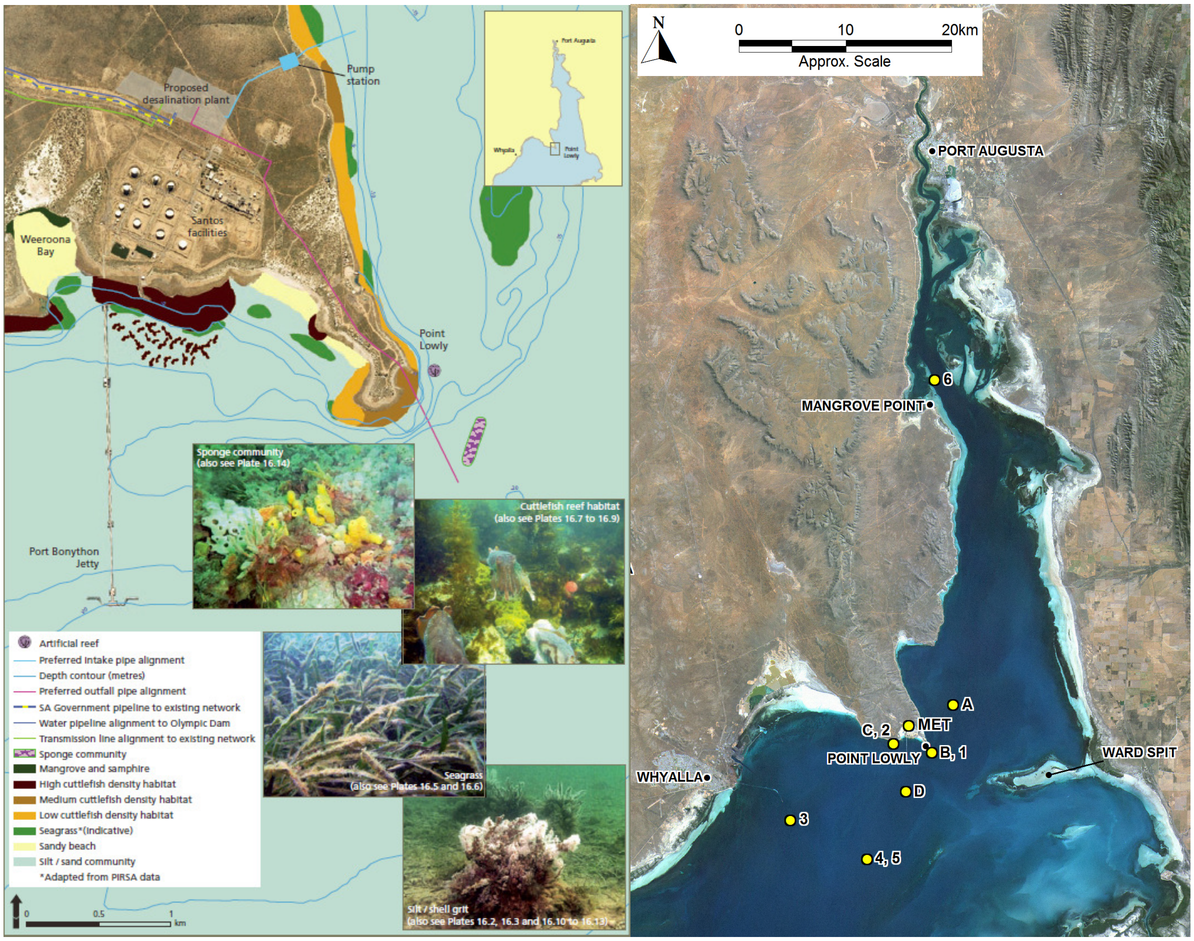

Figure 1 Right Panel: Location of the Desalination Plant and Identified Environmental Receptors (From BHP Billiton 2009). Left Panel: Location of Measurement Stations for Model Validation. Letters Indicate ADCP Locations and Numbers CTD Locations.

Associated with the water production from desalination plants is the potential impact on the marine environment caused by the discharge of concentrated brine to receiving waters, as well as the efficiency of the fresh water production. To these ends, numerical of hydrodynamic and dispersion modelling of the saline water can play a key role in the assessment of the associated environmental impacts and short-circuiting between plant discharge and intake. In the particular case of environmental impacts, the modelling of the brine dispersion aims at providing the spatial-temporal evolution of salinity at which the marine environment would be subjected, and subsequently assist in determining the likely environmental conditions for ecological investigations.

In general, the large scale (far field) hydrodynamic processes are simulated by far field hydrodynamic and transport models, which aim at reproducing the physical processes induced by tides, winds and atmospheric exchange. On the other hand, the local scale or near field process associated with the outfall jet discharge are obtained from so-called near field models.

Fundamentally, a problem of integration arises because the jet or plume dynamics occur on the scale of 0.01 – 10 metres, whereas numerical grids used in hydrodynamic models typically have horizontal scales of 50 – 100 metres (or greater). The initial dilution of brine is thus a sub-grid scale process for the far field hydrodynamic model and involves inherently different physics. As the scales reduce, the non-hydrostatic effects induced by the vertical accelerations of the diffuser discharge become important, and must be included in the nearfield predictions. As a result, the physics and flow equations adopted in the near and far field models are inherently different.

Through detailed studies, we have found that the manner in which near field predictions of brine dilution are linked with hydrodynamic models that examine broader scale advection and dispersive processes is critical to the robust execution of dispersion studies. Further, we have found that this linking can have a significant influence on the spatial distribution of subsequent hydrodynamic model dilution predictions, particularly in the direct vicinity of diffusers.

In this paper, brief descriptions of different linkage techniques reported in the literature are reviewed and their advantages and disadvantages are summarised. This assessment is then used to derive and describe a linkage method appropriate for cases in which sensitive environmental receptors are located relatively near the diffuser. The application of this methodology is then applied to the DPD in Spencer Gulf.

LINKAGE TECHNIQUES

Linkage techniques found in the literature are briefly described below and their applicability to the present study assessed. The proposed new linkage technique is then described.

Insertion Types

Direct Insertion. Direct insertion delivers the 'point of discharge' brine flow rate and salinity (i.e. as leaving the desalination facility prior to delivery to a diffuser) directly to the hydrodynamic model, generally in a single cell, depending on the model resolution. This direct insertion method has been applied as part of the Port Stanvac DSD modelling assessments (SA Water, 2009) where the insertion cells were set to be those encompassing a water depth of ten metres along the diffuser alignment. A slightly different approach is used by Bleninger (2010), in which a nearfield model provides the resulting plume thickness and width, and these are apportioned over a similar volume in the far-field model, but maintaining the discharge characteristics.

Pre-Diluted Brine Insertion. This method delivers a brine flow that has been altered in an attempt to capture the dilution delivered by a selected diffuser arrangement. This method acknowledges the fact that the near field dynamics (especially mixing) are not captured well by far field hydrodynamic models (due to the spatial scale and physics mismatch mentioned above), but that hydrodynamic models will 'see' inflows that have already been subjected to dilution as a result of the action of a diffuser. As such, this linkage technique forces the hydrodynamic model with an inflow boundary condition informed by a (separate) near field model. In essence, this linkage technique draws directly on complementary near field modelling and employs near field results to force hydrodynamic models with appropriately resolved and matched inflow boundary conditions (noting that introduction of pre-diluted water requires a separate extraction to balance mass overall). Such a pre-dilution and extraction technique was successfully applied for the Cockburn Sound modelling studies (Okely et al. 2007). Marti et al. (2011) reported excellent agreement between modelled and subsequently measured salinities and brine dilutions at the Cockburn Sound DPD, having used this pre-dilution technique as the linkage approach in the supporting, and preceding modelling studies.

Flux Approximation Insertion. It assumes that the rate of change of salinity in a hydrodynamic model insertion cell (that contains the diffuser) is a function of the cell salinity (S), undiluted brine salinity (S_b) and flow rate (q_b), and the volume of the selected hydrodynamic model insertion cell (V), such that:

$$\frac{\partial S}{\partial t} = \left(S_b - S\right)\frac{q_b}{V} \qquad (1)$$

This technique has been applied by Kaempf et al. (2009).

Key Characteristics of Above Insertion Methods

Salt Mass Conservation - The direct insertion and pre-dilution insertion techniques ensure salt conservation. The former achieves this by definition as it sees insertion of exactly the pre-diffuser flow rate and salinity to the hydrodynamic model (i.e. S_b x q_b in equation 1). The latter acknowledges that the pre-dilution approach introduces additional salt mass and so sets up appropriate compensatory extractions to exactly conserve mass (Okely et al. 2007). The flux approximation modulates local salinity without addition of water (unless other equations are deployed to do so). Equation (1) can be rearranged to show that the rate of change of salt mass is less than $S_b \, x \, q_b$ (by subtraction of an always positive S from S_b), and as such it is unclear as to whether salt mass is actually conserved in terms of its delivery from the desalination plant. This may warrant further exploration.

Controllable Linkage with Near Field Predictions - It is necessary to ensure that the hydrodynamic model is given as little latitude as possible to auto-determine the boundary condition flows (and hence dilutions and salinities) at the site of the diffuser for subsequent advection and dispersion through its domain. In other words, maximal control over the flow, dilution and salinity at the hydrodynamic boundary insertion location(s) is required to minimise uncertainty and avoid unnecessary conservatism in dilution predictions at sensitive receptors relatively close to the diffuser.

The direct insertion method does not readily allow for controllable linkage of near field and hydrodynamic models. For example, in the Port Stanvac modelling study (SA Water 2009) and the technique described by Bleninger (2010), it is understood that brine was directly inserted (i.e. not pre-diluted) to the hydrodynamic model over a range of cells both horizontally and vertically. As there is no explicit pre-dilution technique applied in the model, the only dilution available is numerical. Specifically, the collapse (reported to be in one time step in SA Water 2009) and associated mixing of the vertically inserted brine concentrate within the hydrodynamic model set the effective insertion flow dilution and salinity at bed level for subsequent advection and dispersion at depth. Thus, this boundary condition was not entirely controlled with reference to near field predictions. It is not our intent here to make an assessment of the suitability of this approach for those studies, but rather to flag the use of this technique with respect to the proposed discharge at Port Bonython.

The pre-dilution method does make an attempt to link near field and hydrodynamic models with a degree of control. It does so by delivering diluted brine (with the dilution determined by a near field model) directly to the hydrodynamic model. A constant pre-dilution was adopted by Okely et al. (2007), which is most likely in response to the relatively uniform tidal/wind driven currents (hence near field performance) in Cockburn Sound. The initial pre-dilution is often based on background (baseline) salinities.

The flux approximation method takes no account of near field modelling, so is unrelated to any near field modelling predictions.

Controllable Dynamic Response to Tidal Forcing - An important requirement for the current study at Port Bonython was to be able to dynamically vary, in a controlled fashion, the hydrodynamic model boundary condition for flow, dilution and salinity, primarily to capture variations in the performance of diffuser dilution as a result of varying tidal current magnitudes. Notably, our measurements of tidal currents at the site (the duration of which spans more than one year and includes several separate deployments at multiple locations) show that the range in ambient tidal velocities is large at the point of interest, with 50^{th} and 99^{th} percentile velocities over the water column being 0.49 and 1.18 m/s, respectively. The direct insertion method does not support such control, and it is not clear to the authors how the initial numerical dilution and/or subsequent collapse-driven mixing could controllably vary the resultant dilution as a function of current speed, and importantly, how this would then match the dilutions to near field dilution predictions in a controllable fashion.

The pre-dilution method, as encountered by the authors to date, has been implemented using a constant (temporally invariant) pre-dilution, so has not, so far, allowed for dynamic alteration of injected dilutions. The flux approximation method takes no account of near field modelling so does not have the ability to deliver a controlled time variant flow, dilution and salinity that is tied to near field modelling studies.

Hydrodynamic Model Grid and Time Step Independence - This is required to ensure that grid and time step related numerical artefacts are minimised or eliminated entirely, primarily to reduce associated predictive uncertainties. In addition, it is considered important to be able to apply the same methodology to different hydrodynamic models (or model configurations) and facilitate consistency of prediction without needing to retrospectively alter a grid dependent insertion method to suit.

The direct insertion method is grid dependent to the extent that the initial numerical dilution that occurs when the brine concentrate is injected into the model varies with varying model grid size (both horizontally and vertically). The starting dilution varies with grid size as the same brine concentrate is spread over varying initialisation volumes as grid size changes. This variation applies in the horizontal and vertical, and the effect becomes more pronounced as the incremental brine concentrate volume becomes smaller relative to the volume of the initialisation cells. Similarly, it is time step dependent in that it numerically mixes a given volume of brine concentrate within a suite of pre-selected cells. A doubling in time step, for example, would result in a doubling of the volume of brine concentrate injected into the suite of insertion cells, and a doubling of the resultant initial brine concentration computed by the hydrodynamic model by virtue of numerical dilution, advection aside and assuming zero brine background conditions.

The pre-dilution insertion technique is also somewhat susceptible to grid and time step dependence, but to a lesser extent than the direct insertion method. This is because the pre-dilution volumes (for a given brine concentrate flow rate) are generally much larger than the concentrate flow rate itself (by a factor of the dilutions achieved by a diffuser), so form a greater proportion of the insertion cell volumes within a given time step. In time, this method ‘fills’ the insertion cells with diluted brine (representing diffuser performance) at a rate greater than the direct insertion method. This increased rate is at least equal to the worst dilution predicted by near field modelling.

Notwithstanding this, however, both the direct and pre-dilution techniques mix inserted brine with some volume of background water that (potentially) has already felt the influence of previously discharged brine. The extent to which this mixing occurs is different in the two techniques by a factor related to the performance of the near field diffuser.

The flux approximation method is grid dependent as the insertion cell volume (V) appears explicitly in the flux equation (equation 1). For example, as the insertion cell volume reduces, the rate of change of salinity in that cell (and hence the predicted salinity) increases. The flux approximation method employs a rate of change approach to salinity in a receiving cell, so it is possible (although unclear) that this method is also time step dependent.

An Improved Linkage Technique

Given the above, a linkage technique was developed that preserves discharged salt mass whilst ensuring delivery of flows, salinities and dilutions to the hydrodynamic model that directly reflect near field (CFD) modelling predictions across a range of background tidal conditions. The method is an extension of the pre-dilution technique described above with provisions for the variability of dilutions generated by the ambient flow conditions. In this case, CFD simulations were used, but the method could be applied seamlessly using any nearfield modelling platform.

In essence, the method consists of integrating the near and far field models interchangeably, such that the farfield model provides the environmental conditions for the nearfield model, which in turn, provides the required dilutions to be adopted at the outfall discharge boundary condition in the farfield model. Use of far field modelling results requires that the farfield model be thoroughly validated against field data for a range of conditions. In the case of Spencer Gulf, the tides represent the main forcing of the Gulf dynamics, such that environmental conditions were described in terms of depth-averaged velocity percentiles for each of the ebb and flood phases.

CFD simulations were then set-up and executed taking these velocities as boundary conditions, such that dilution predictions were casted as a function of depth-averaged velocities in the form of a "lookup table". A baseline farfield simulation was then executed, such that background velocities could be used as input to obtain the dilutions given in the lookup table. Taking into consideration the background simulation, salinities and other scalar fields at the proposed diffuser boundary were computed as a function of these dilutions. The fluid entrained in the plume was assumed to have scalar (i.e. temperature, salinity, and tracer concentration) characteristics of the depth-averaged scalars in the background (baseline) simulations. For DPD this assumption is consistent with the CFD prediction that plume travel paths reach higher parts of the water column and as such plumes entrain relatively unaffected background waters, once they are well clear of the bottom salinity layer. This has also been qualitatively confirmed by field experiments presented by Okely et al. (2007b). Accordingly, the outfall discharge was increased in such a manner to reflect the entrained ambient fluid.

Of particular importance is the derivation of tracer concentrations and salinities, which under this method directly reflect the spatially and temporally variant performance of the diffuser under the full range of tidal current conditions. It is also noted that the dilutions predicted by CFD are conservative (BHP Billiton 2011a).

As discussed above with reference to the work undertaken in Cockburn Sound (Okely et al. 2007b), a salt sink was introduced to remove excess entrained salt (generated via pre-dilution). In the present methodology, the required sink is distributed at specified cells in the domain in such a way that the sink flow rate to balance the salt mass can be accurately computed.

SPENCER GULF DPD MODELLING

Far Field Modelling

The Estuary, Lake and Coastal Ocean Model – ELCOM (e.g. Botelho et al. 2007, Barry et al. 2010) was used to simulate the far-field hydrodynamics and transport in Spencer Gulf. The model was validated against several data sets spanning seasonal and tidal time scales and over several spatial scales in the Spencer Gulf. Model resolution focused in the location of the diffuser (40 m) and a time step of 24 s was used in the simulations. Full description of the model set-up and validation exercise is presented in BHP Billiton (2011b). Here, we present an illustration of the model comparisons against a sub-set of a 40-day data set collected near the proposed diffuser location (Figure 2). The period illustrates the model's ability to capture the spatial variability of the dynamics in the location of the diffuser (site B) and near sensitive receptors (i.e. giant cuttlefish habitat, site C) during both spring and neap tides.

Near Field Modelling

Nearfield modelling was conducted in the software OpenFOAM (Open Field Operation and Manipulation) using steady state (nonhydrostatic) flow equations adopting the effects of salinity and temperature in the density field. A κ–ω formulation was used for the turbulent closure scheme.

An adaptive mesh refinement technique was used to dynamically and iteratively adjust the mesh during the computations, in such a way to provide maximum resolution in the vicinity of the diffuser ports and in regions where salinity gradients and velocity shear were above a pre-defined threshold. Over 2.5 million cells were used in the final computational domain with finer cells adjacent to the diffuser ports being the order of 15 mm. Computations were processed on a multi-CPU computer with 128 processors.

A rigid lid approximation was used to represent the free-surface. Representative profiles for each depth-averaged velocity percentiles provided boundary conditions for one the sides of the model domain (i.e. the one in the upstream side of the diffuser according to the tidal flow direction). The boundary condition at the other side was unconstrained in velocities except that total volume flux was conserved. The dilutions that were adopted in ELCOM were obtained when the steady state solutions and further mesh refinement converged to same results. Further details of the CFD model and its validation are presented in BHP Billiton (2011a).

Methodology Application

The application of the modelling methodology described above was adapted to a set of diffuser configurations of the Spencer Gulf DPD. This allowed the diffuser configuration to be optimised and sensitivity analyses of the adaptive pre-dilution insertion method to be performed.

The diffuser configuration investigated herein consisted of a 200m linear diffuser aligned approximately normal to the tidal flow direction (SW-NE direction, see Figure 1). A total of 50 alternating sides ports at a 60^{o} angle with the horizontal were equally distributed over its length. It is noted that this configuration (and results presented) do not reflect the final adopted and optimised diffuser design and neither the final location of the proposed diffuser (see BHP Billiton 2011a).

The CFD model domain consisted of a Cartesian box aligned with the diffuser, spanning 160 m either side of the centre of the diffuser alignment in both directions (i.e. producing a 320 m wide domain). The top surface of the model was the z = 0 m (Australian Height Datum) plane and the bottom surface was fitted to digital elevation model (DEM) data from the ELCOM model (which is derived from BHP Billiton survey data and other supplementary data sets).

Modelled velocities at Site B (Figure 2) were used to derive the velocity profiles for the nearfield boundary conditions. Examples of the resulting dilution fields from the CFD simulations are illustrated in Figure 3. The light blue surfaces indicate the 45:1 dilution iso-surfaces and the vertical curtains show the dilution field 100 m downstream of the diffuser alignment. Note that the colour bar was scaled from the minimum dilution seen on the 100 m curtain to an upper limit of 1000:1, and that the actual currents speeds for ebb and flood were not necessarily equal and opposite.

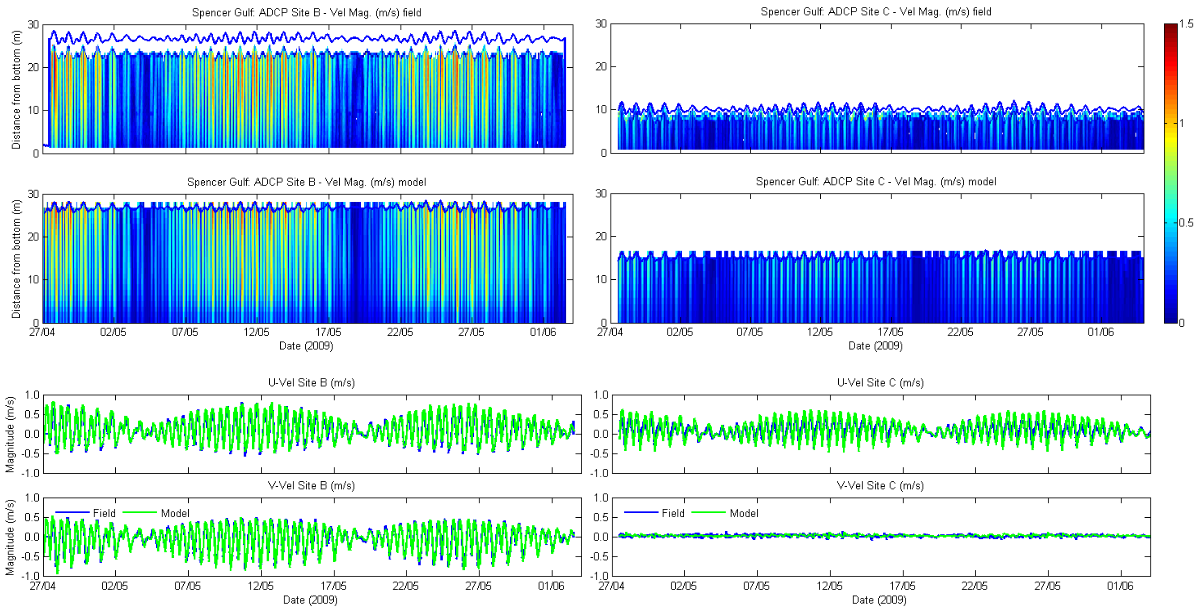

Figure 2 Model Comparisons to Field Data at Sites B and C (see Figure 1). Upper Panels: Velocity Magnitude. Lower Panels: Depth-Averaged Velocity Components.

From results similar to the ones presented in Figure 3 for other velocity percentiles, dilutions as a function of the cumulative distributions of depth-averaged velocities were obtained (Figure 4, i.e. a graph of the "lookup" table). Example of boundary conditions for discharge rate and tracer (*C*) are presented in Figure 5. The variations that are seen in Figure 5 were associated with slack and running water and the spring-neap cycle modulation, and reflected the range of environmental conditions and associated nearfield dilutions to which the discharge would be subjected.

In the farfield model, the salt sinks were located in such a way that: 1) they occupied a relatively broad area, such that the sink discharge would have minimal disruption to the local hydrodynamics; 2) they were, however, within the general vicinity of the proposed outfall such that excess salt did not accumulate in the Northern Spencer Gulf; but 3) the outflow cells were specified at distance from the outfall (i.e. away from the deep basin where dilutions were relatively low) and at least 5 m above the seabed where salinities at the outflow cells were similar to the reference simulations. This placement ensured that the salt sink could be accurately computed.

FARFIELD MODELLING RESULTS

Control Points

Figure 6 presents salinities and dilutions at the bottom at different control points from simulations spanning a 40 day period (03 December 2008 to 13 January 2009). The simulations include a reference background case, the effect of discharge using a direct insertion method case, and the effects of the discharge using the adaptive linkage method with an 8 s and 24 s time step cases.

It is readily seen that salinities from the direct insertion method (red line) were generally larger than the adaptive linkage method (cyan and green lines) and conversely, dilutions were lower. The closer to the diffuser the control point the more marked the differences. Well away from the diffuser (~1.5 km at point L), differences between methods were not relevant and very similar to background conditions (blue lines). However, for all other points, including point B that was located at approximately 600m from the diffuser, the direct insertion method predicted dilutions lower than the minimum dilutions predicted by nearfield CFD simulations. The adaptive linkage method simulations tracked each other very closely, and did not present dilutions lower than the nearfield simulations. These results indicated that the adaptive method is, at least approximately, time step independent.

Predictions with the direct insertion method were conservative at sensitive receptors near the diffuser (points SP denote sponge communities), indicating unrealistic exposure to elevated salinities. Conversely, adopting the adaptive insertion method, although still conservative (see BHP Billiton 2011a), more realistic predictions could be made, such that the receptors were exposed to elevated salinities less frequently. Also the adaptive linkage simulations predicted significantly lower salinity peaks in comparison to the direct insertion method (Figure 6).

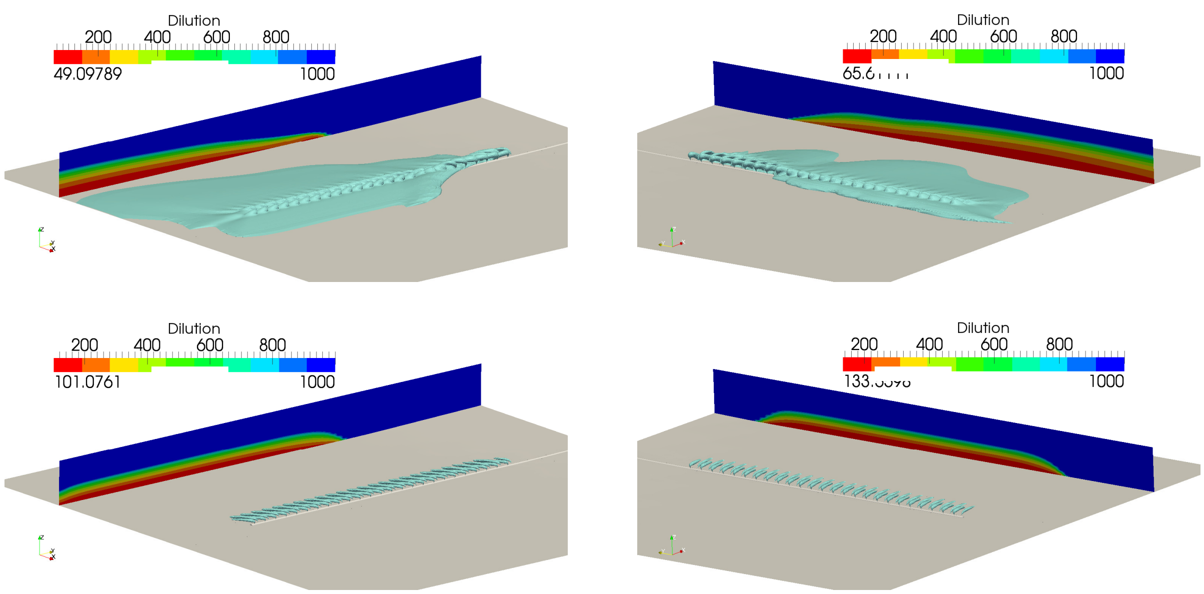

Figure 3 Dilution Fields Obtained from the Nearfield CFD Simulations. Top Panels: Associated with 30th Percentile Velocity Profiles. Lower Panels: Associated with 70th Percentile Velocity Profiles. Left Panels: Ebb Tides. Right Panels: Flood Tides. See text for details.

DPD Footprint

The discharge footprints as given by the 1st percentile dilutions are presented for the two different methods in Figure 7. It can be seen that footprint areas given by the direct insertion were larger than the areas given by the adaptive method, particularly for the lowest dilutions. The red area for example, shows dilutions lower (i.e. impossible) than the worst case scenario of CFD predictions, which do not appear in the adaptive linkage method. Superimposed on the footprints are the contours of dilutions 1 to 45 and 1 to 85 at the time in which the largest areas under these dilutions were predicted (approximately 22 December 2008 18:00). These dilutions were derived from ecotoxicology tests that indicated that 95% and 99% of species, respectively, would be relatively unaffected by the desalination discharge (see BHP Billiton 2011c for details). Table 1 indicates that both footprints and instantaneous areas for these dilution contours were 17% to 48% smaller adopting the adaptive linkage methods.

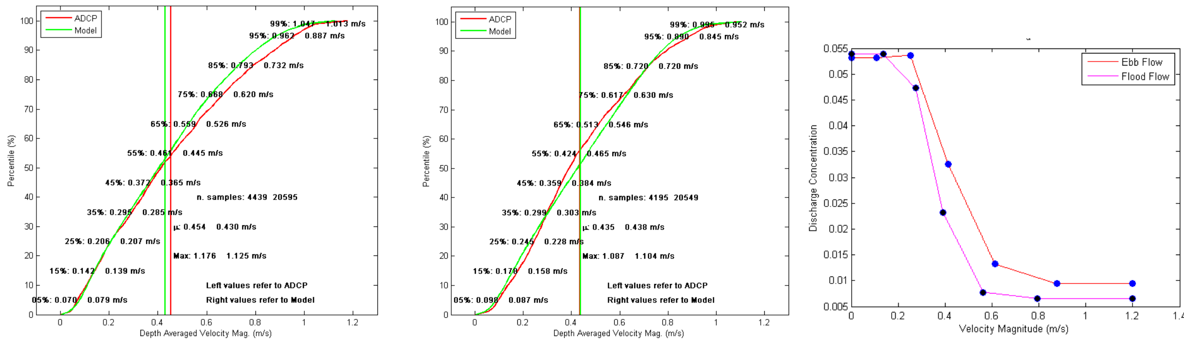

Figure 4 Left Panel: Cumulative Distribution of Depth-Averaged Velocities at Discharge Location during Ebb Tides. Centre Panel: Flood Tides. Right Panel: Dilutions as a Function of Depth-Averaged Velocities Obtained from CFD Simulations.

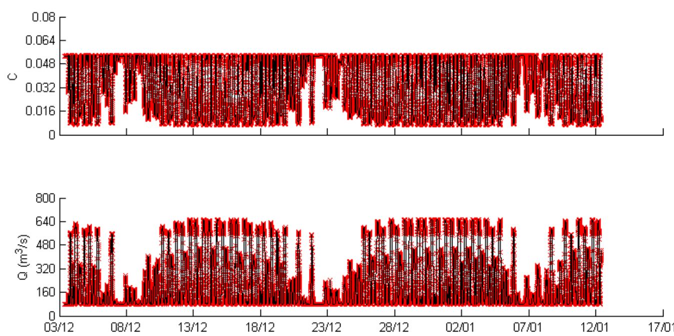

Figure 5 Example of Discharge Rate and Concentration Boundary Conditions.

CONCLUSIONS

An improved adaptive linkage method between near and far field models was developed such that more realistic dilution and salinity estimates of brine dispersion could be obtained. The new method was shown to have desired properties in terms of representing more accurately the predictions of the nearfield model, conserving salt and being independent of either grid size or time step. The methodology was applied to a proposed desalination plant discharge in Spencer Gulf, South, Australia. For the model configurations studied, the new linkage method, in comparison to direct insertion methods used in far field models, was shown to be less conservative in terms of salinities, dilutions, and footprint areas.

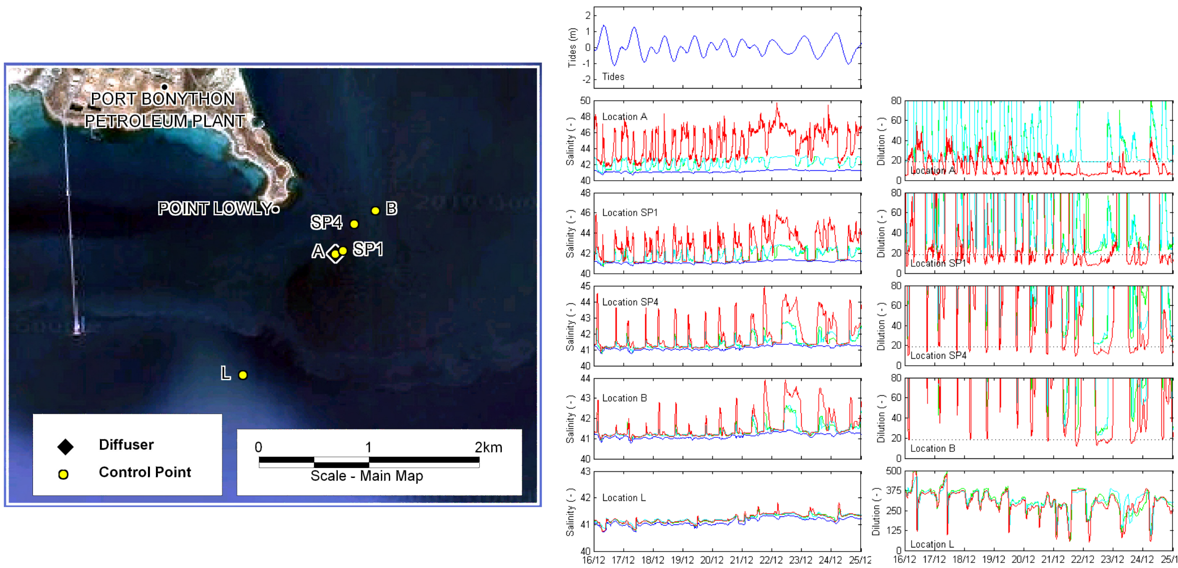

Figure 6 Left Panel: Control Point Locations. Centre Panel: Salinities at Control Points. Right Panel: Dilutions at Control Points. Blue lines are background conditions, red lines are results of the direct insertion method, cyan lines are the adaptive linkage method using a 8s time step, and green lines are the adaptive linkage method using a 24s time step, the black dotted line is the minimum outfall dilutions.

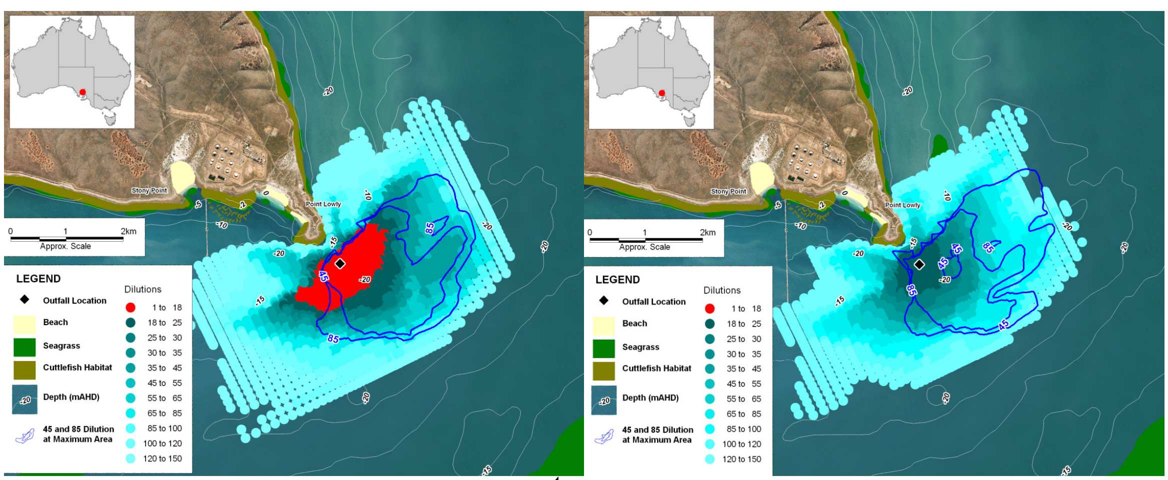

Figure 7 Discharge Footprint given by 1st Percentile Dilution Maps. Left Panel: Direct Injection Method and Right Panel: Adaptive Injection Method.

Table 1 Footprint Area and Areas at the Time of Largest Area under 1:85 Dilution (Instantaneous).

Dilution	Direct Injection		Adaptive Injection	
	Footprint (1st Percentile)	Instantaneous	Footprint (1st Percentile)	Instantaneous
	(Ha)	(Ha)	(Ha)	(Ha)
45:1	460	360	240	300
85:1	860	580	620	430

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