Three modelling techniques used in Australia to model desalination plant brine dispersal in both the near-field and far-field

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Abstract
In the past five years six major seawater reverse osmosis desalination plants have been built to serve Australia's largest coastal cities, with smaller desalination facilities proposed for mine sites and remote towns. With strict brine dispersion criteria imposed by Australian Environmental Protection Agencies, a range of modelling tools have been used to develop engineering solutions. This paper presents the use of three dispersion prediction tools, with reference to ease of use and accuracy.

The 'Roberts empirical mixing model' was used by Sinclair Knight Merz to predict near-field mixing for the concept and detailed design of the Gold Coast and Sydney desalination plants, and for tender designs for Melbourne and Adelaide desalination plants. While flexible and rapid in application, drawbacks related to model simplicity include the inability to analyse complex interactions between plumes from multiport structures. However, a yearlong monitoring program recently completed at the Gold Coast desalination plant has shown that the predicted mixing ratios have been met and exceeded for a range of actual ocean conditions and plant flows.

In addition, brine plume dynamics for the Adelaide and Melbourne desalination plant tender designs were modelled by computational fluid dynamics (CFD) using ANSYS FLUENT™ software. When calibrated to empirical data the model provided an acceptable model result, though somewhat under-predicting mixing in the near field. In the mid- to far-field, the CFD model did not replicate the expected decay of turbulent mixing recorded. With these limitations, FLUENT can be used to give an indication of multi-plume dynamics and interactions in both calm waters and under the influence of currents.

For far field plume dispersion modelling, Sinclair Knight Merz has engaged the specialist oceanographic modelling services of GEMS. Given brine plume data, and historic current and meteorological data, GEMS' GCOM3D™ software can be used to produce a continuous animation of brine plume fate, including imagery indicating the percentage time where plume dispersion may not meet regulatory conditions.

These three modelling techniques have allowed desalination plant marine outfalls to be designed with confidence that the required dispersion criteria can be met.

Keywords
Desalination; brine plume dispersion; marine outfall; hydraulic modelling; computational fluid dynamics; ANSYS FLUENT; GCOM3D

INTRODUCTION

Australia is the driest inhabited continent, and although the continent has an area approximately the same as mainland USA, low rainfall across a large proportion of the continent has resulted in a much smaller population of only 22 million people. 80% of the population lives near the coast, and all State capital cities are coastal. Periodic extended droughts have embedded the value of water in the Australian psyche, and the most recent extended drought in south eastern Australia from 2003 to 2010 combined with continued declining rainfall in Western Australia since the 1970's has prompted the construction of desalination plants in Perth, Brisbane-Gold Coast, Sydney, Melbourne and Adelaide.

As summarised in Table 1, when completed to ultimate capacity the Australian capital city desalination plants will supply a total of nearly 2 GL/day of drinking water. During drought conditions, with desalination plants running at ultimate capacity, approximately 25% of Australian residential water use could be supplied with desalinated seawater from the major plants. In addition, numerous smaller plants already supply some regional centres and mining operations, with more likely to be built in the future. These plants will discharge a significant volume of seawater concentrate to the coastal environment and to prevent environmental harm each of the State Environmental Protection Agencies (EPA's) have imposed strict restrictions on the outfall systems in the form of allowable discharge locations and minimum concentrate dilution ratios required within specified distances of the outfall.

To achieve the required dilution ratios, each of the major Australian desalination plants has utilised a multi- nozzle dispersion outfall system, with seawater concentrate expelled at high velocity at multiple locations, achieving dispersion by turbulent mixing. Modelling of the seawater concentrate outfall system demonstrating compliance with the required dispersion criteria has been necessary to gain environmental (and construction) approvals, as well as to avoid potentially costly breaches of licence conditions during operations.

Table 1. Australian capital city desalination plant construction dates and capacities (updated from Alspach, *et al* (2009))

City	Plant Site Name	On Line	Nominal Capacity (ML/d)	Ultimate Capacity
Perth 1	**Kwinana**	2006	123	123
Brisbane / Gold Coast	**Tugun**	2008/9	125	170
Sydney	**Kurnell**	2009/10	250	500
Perth 2	**Binningup**	2011	137	274
Adelaide	**Port Stanvac**	2012	280	280
Melbourne	**Wonthaggi**	2012	420	560
				1907 ML/d

APPLICATION OF ROBERTS' EMPIRICAL MODEL

It is the authors' experience that during the tender and concept design phases of large SWRO plants, many nozzle configurations and diffuser arrays need to be trialled to determine the arrangement that best suits the regulatory conditions, the local coastal environment, and the project budget. During this time, the flow rates of seawater concentrate to be dispersed may change several times before designs are finalised. This fluid design environment, typically coupled with short design timeframes, means that a flexible dispersion model is required.

When designing the outfall systems for the Gold Coast and Sydney desalination plants, and when tendering for Melbourne and Adelaide desalination plants, Sinclair Knight Merz (SKM) applied the empirical model described by Roberts *et al* (1997). This model relates key seawater concentrate plume statistics to the jet densimetric Froude number as shown in Equation 1, where u is discharge velocity, g is acceleration due to gravity, d is nozzle diameter, ρ_0 is initial density of the discharge jet, and ρ_a is ambient density of the receiving water.

$$F = \frac{u}{\sqrt{gd\frac{(\rho_0-\rho_a)}{\rho_a}}} \tag{1}$$

The key parameter from Roberts *et al* (1997) utilised in design was Ultimate Minimum Dilution (S_m), given by $S_m = F \times 2.6 \pm 15\%$, but for some plants, such as the Gold Coast plant, Terminal Rise Height (y = 2.2F) was also an important design parameter. Impact Dilution (S_i) was of interest but not a specific design criteria as the impact zone in each case was well within the allowable mixing zone, which was designated based on distance to reach Ultimate Minimum Dilution (x_m).

In Roberts *et al* (1997), all equations are based on a nozzle angle of 60° from horizontal, as this was seen to be most effective for mixing. So that the equations may be applied, and to promote mixing, Australian desalination plants have adopted a nozzle angle of 60°. However, further research by Nemlioglu and Roberts (2006) has shown that mixing is maximised across a relatively large range of nozzle angles, from $30° < \theta < 75°$, and that in this range Impact Dilution (S_i) is 1.6 x F, an increase in the impact point dilution estimate of 6%. As Nemlioglu and Roberts (2006) did not report an updated S_m parameter, parameters from Roberts *et al* (1997) were used in all outfall designs completed by SKM.

Based on the equations given above, the Gold Coast desalination plant diffuser array was designed as two 1.2 m diameter manifold arms extending from a central 'diffuser head', and is shown in Figure 1. From each of the manifold arms, ten glass reinforced plastic (GRP) nozzles (Figure 2) were attached alternating at 60° from the horizontal. High velocities were required through each nozzle to generate the 40:1 ultimate dilution required by the Queensland EPA, which subsequently generated large head losses. Head loss through the Gold Coast desalination plant outlet system was an important design constraint as the plant site is only +7 m above sea level and the outfall was gravity driven, restricting the head loss allowable through the outlet system during commissioning and flow bypass events. Achieving high velocity discharges through the nozzles to generate a sufficient mixing while maintaining low head loss presented a significant design challenge.

As the number of nozzles, spacing, and diameter were all variable during the design phase, a flexible Excel™ based design tool was created incorporating both hydraulic equations and the empirical mixing relationships presented by Roberts *et al* (1997). With flow through each nozzle and the nozzle diameter known, it was a simple task to calculate the densimetric Froude number of each nozzle and thus the expected Ultimate Minimum Dilution. The number of nozzles and diameters and spacings were modified to generate several appropriate solutions, which were then tested in more detail for a range of flow conditions, and construction costs were estimated. The simplicity of the mixing equations allowed many potential designs to be quickly compared, which in a flexible design environment was an advantage over slower modelling methods involving computational fluid dynamics (CFD).

Since completion of the Gold Coast desalination plant in 2009, recent monitoring has confirmed that modelled dilution ratios are being achieved. During a year-long study measuring salinity, Boerlage *et al* (2011) found that in practice it was difficult to detect the seawater concentrate plume due to natural fluctuations in salinity and haloclines. These produced data noise and masked small differences in salinity between the plume (measured 40 m from the discharge site) and ambient seawater (measured at control sites 500 m from the discharge location). Currents and wave movements also resulted in varying dilution through time, and drift in instrument response meant that not all data were considered reliable. Though complicated by the fluctuations in measurements, the conclusion was that the diffusers are achieving dilutions above the modelled dilution, giving real world validation to the equations presented by Roberts *et al* (1997).

Figure 1. 'Diffuser head' and 'arms' prior to installation on seabed

Figure 2. GRP flanged nozzles prior to installation

COMPUTATIONAL FLUID DYNAMICS USING FLUENT

Australian EPAs have accepted near-field seawater concentrate discharge modelling based solely on Roberts *et al* (1997). However, to increase confidence regarding the interactions of multiple plumes, and visualise the processes at work, computational fluid dynamics (CFD) models were developed by SKM for the Adelaide and Melbourne desalination plant tender designs using ANSYS FLUENT™ software.

Prior to applying the software to specific desalination plant designs, the software was tested with both the Renormalized Group (RNG) k-ε turbulence model of Yakhot *et al* (1992) and Yakhot & Orszag (1986), and the Shear Stress Transport (SST) k-ω turbulence model of Menter (1994), to determine which turbulence model would enable ANSYS FLUENT to best replicate the experimental results described in Roberts *et al* (1997) and Nemlioglu and Roberts (2006). The RNG k-ε model predicted impact dilutions approximately half those reported by Roberts *et al* (1997), so the SST k-ω model was adopted (Seil & Zhang, 2010). However, even when the SST k-ω turbulence model was calibrated against the experimental measurements, the model under-predicted impact point dilution, and failed to account for the decay of turbulence at distances greater than x/dF=7, as seen in Figure 3. Based on these results, it would appear that the ANSYS FLUENT CFD (SST k-ω) model can be used to give a conservative estimate of dilution only in the range $0 \leq x/dF \leq 7$.

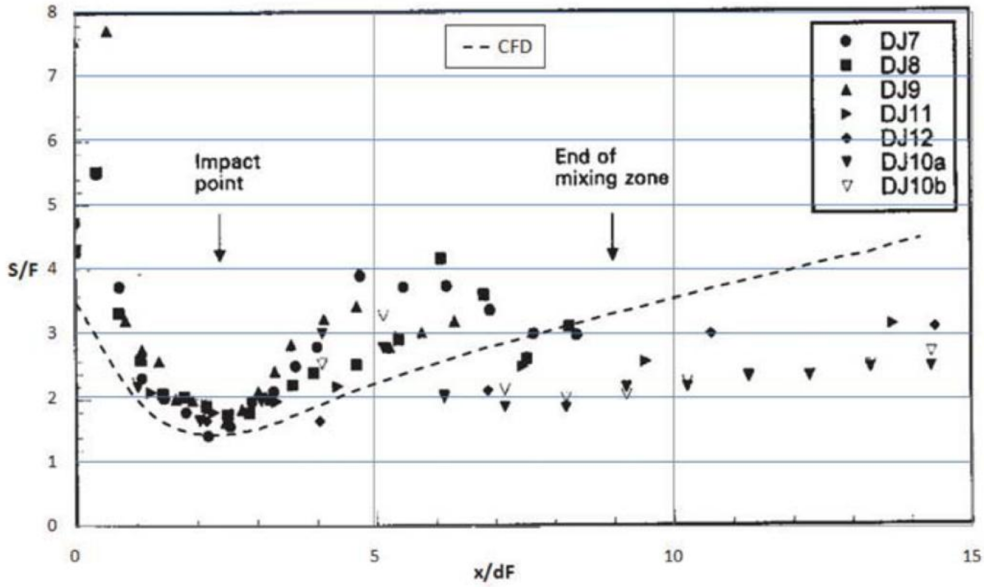

Figure 3. Comparison of experimental dilution from a single nozzle discharge at 60° from the horizontal measured by Roberts *et al* (1997) with ANSYS FLUENT CFD model results using the SST k-ω turbulence model (Seil & Zhang, 2010).

A time-averaged salinity concentration along the centreline of a single plume is shown in Figure 4, where it can be seen that the CFD model gives the expected plume shape, and shows the development of a dense seabed layer. One interesting effect noted in the CFD model was the re-entrainment of previously mixed seawater concentrate into the plume when the dense seabed layer spread back to the nozzle location, with a subsequent build-up of salinity over time until a steady-state was reached. Modelling this effect is not possible in many Lagrangian plume models, justifying the use of more computationally expensive CFD modelling for scenarios where currents are very small (Seil & Zhang, 2010).

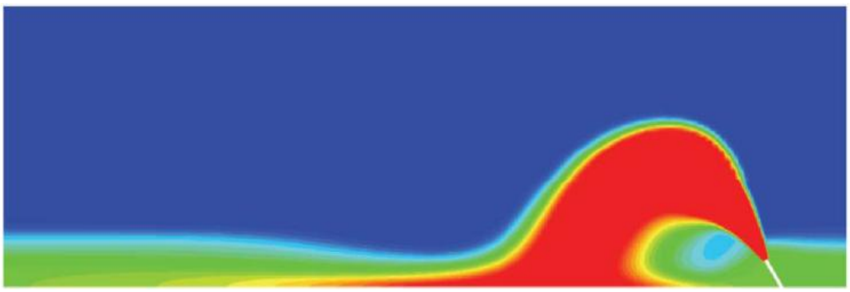

Figure 4. Salinity on the centreline of a plume modelled using ANSYS FLUENT (after Seil & Zhang, 2010)

After investigating many possible diffuser and nozzle arrangements for the Adelaide desalination plant tender design using an Excel™ based model (similar to that for the Gold Coast desalination plant), the preferred design was modelled using the calibrated ANSYS FLUENT model to investigate the effects of adjacent plume interaction and the impact that currents had on the size of the mixing zone. Figure 5 shows the plume from a 10 nozzle diffuser array, in which it can be seen that the nozzles are spaced sufficiently far apart to prevent plume convergence prior to impact with the seabed in zero current conditions, but that post-impact the plumes merge, causing a reduction in post-impact mixing. Similar visualisations were also created for cases with non-zero currents to determine the area that the mixing zone might encompass under varying conditions.

As it was known that the CFD model under-predicted impact point dilution and over-predicted the Ultimate Minimum Dilution, dilutions given by the Roberts *et al* (1997) model were used for design decisions, but the CFD model was helpful in confirming that these dilutions were not being compromised by complex plume interactions.

As with the CORMIX investigations reported by Bleninger and Jirka (2008), the CFD model was seen to give good estimates of terminal rise height and impact point even while under-predicting initial turbulent mixing. Setting up and running ANSYS FLUENT models took a long time, making the use of ANSYS FLUENT as the primary diffuser design tool impractical during the early stages of tender design. However, once the rapid design development phase was complete and preferred diffuser arrangements were known based on Excel™ based models, the use of CFD was valuable in refining the preferred option and in understanding near-field plume interactions and mid-field seawater concentrate fate in more detail.

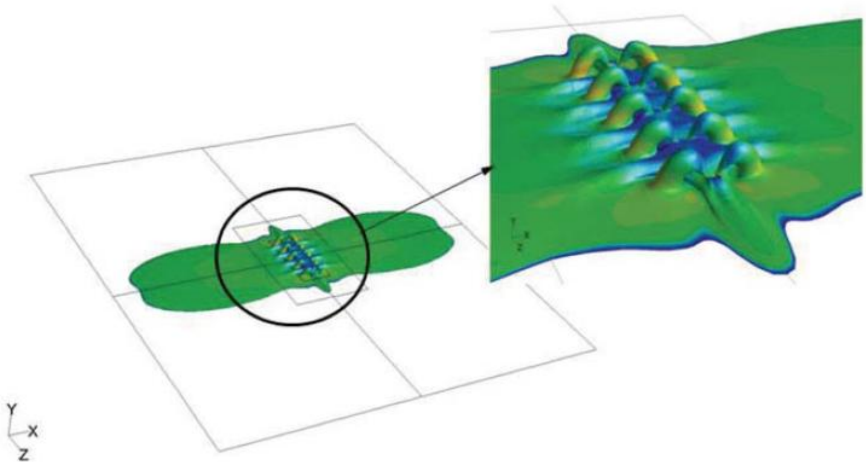

Figure 5. Shape of a 10 nozzle diffuser array plume at zero current (after Seil & Zhang, 2010)

FAR FIELD MODELLING WITH GCOM3D

When investigating the far-field seawater concentrate dispersion using measured bathymetry and long term ocean current profiles, specialist oceanographic hydrodynamic models are required for practical modelling as general purpose CFD models such as ANSYS FLUENT are not practical due to long run times, inaccuracies in the far-field, and the requirement to model diverse current velocities and directions. For site selection studies prior to desalination plant detailed design, SKM has had specialist hydrodynamic modelling undertaken by GEMS using GEMS 3-D Coastal Ocean Model (GCOM3D).

GCOM3D is a three-dimensional, ocean-circulation model that determines horizontal and vertical circulation due to wind stress, atmospheric pressure gradients, astronomical tides, quadratic bottom friction and ocean thermal structure, and has been formulated as a re-locatable model which can be applied anywhere in the world using tidal constituent and bathymetric data derived from global and local databases.

The model operates on a regular grid in the horizontal plane using a varying number of constant thickness layers depending on the depth of water. This scheme decouples surface wind stress and seabed friction and avoids the bias of current predictions for a particular layer caused by averaging of currents over varying depths, as used in sigma co-ordinate and "depth-averaged" model schemes. In the upper water column layers are typically a few metres apart, increasing to several hundred metres in deep waters.

The model has been running in real-time at the Australian Maritime Safety Authority in Canberra since 1998 where it is used by Australian Search and Rescue, and has been incorporated into the U.S. Navy's 'Globally Relocatable Navy Tide/Atmosphere Modeling System' (PCTides).

In 2010 GCOM3D was used by SKM and GEMS to compare three sites for a small desalination plant (20 kL/day) to serve a rural community in regional South Australia. Two of the sites were located in a bay, and the third off a rocky cliff. One purpose of the study was to determine whether seawater concentrate released in the bay would be flushed out, or accumulate over time. To answer these questions, GCOM3D was set up with a coarse grid of South Australian coastal waters, in which fine grids were nested at each of the study sites. One year (2009) of continuously measured tidal and current data was applied within the coarse grid to create appropriate boundary conditions for the fine grids. As the study was still at the pre-feasibility stage, detailed bathymetry was not available and so marine chart data was used to generate bathymetry within each of the fine grids. As wind gauges did not exist at the sites, wind shear forces in the fine grids were calculated in the model based on a MESOLAPS wind data series for the same data period as the tidal and current data. To check that this model setup accurately predicted currents, GPS tracked ocean surface drifters were released during both summer and winter conditions, and model outputs were compared favourably with the measured tracks.

By introducing dense seawater concentrate into GCOM3D at possible desalination plant outfall locations, the model was used to show the dispersion and transportation of the concentrate due to bed slope and currents. The model can be coupled with a Lagrangian plume model (Plume3D), but for the purposes of this preliminary study it was assumed that the discharge would be via an open pipe with no nozzles, so the effectiveness of the ocean turbulence and currents in dispersing the concentrate could be established.

Instantaneous dilutions due to current and bathymetry are shown in Figure 6 for one particular time during the 2009 data series. It can be seen that at the site shown on the left (open, exposed water) the plume very quickly becomes undetectable, whereas plumes from the two sites shown on the right (in a protected bay) spread further before becoming undetectable. However, in both cases dilution above the South Australian EPA condition of 50:1 is achieved very close to the discharge site such that the region of high concentration is not visible on these plots.

Results were then time averaged over the 12 month simulation period to give plots showing the percentage of time the EPA requirement of 50:1 dilution would be met. Figure 7 shows that for each of the three sites the 99% compliance zone is drawn out along the coast, and that the two sites in the bay shown on the right have irregularly shaped mixing zones. It is expected that if a diffuser arrangement were included in these models, the 99% compliance zone would be smaller. However, these results as they stand show that the small discharge volume is dispersed well in any case at each of the three sites, especially considering that the 95% compliance zone in each case is a small circular zone near the outlet with diameter less than 200 m.

In addition to assisting with site selection so that sites with poor flushing characteristics can be avoided, the GCOM3D results will be useful in preparing reports for the EPA to allow approvals to be granted, with subsequent progression of the project into design.

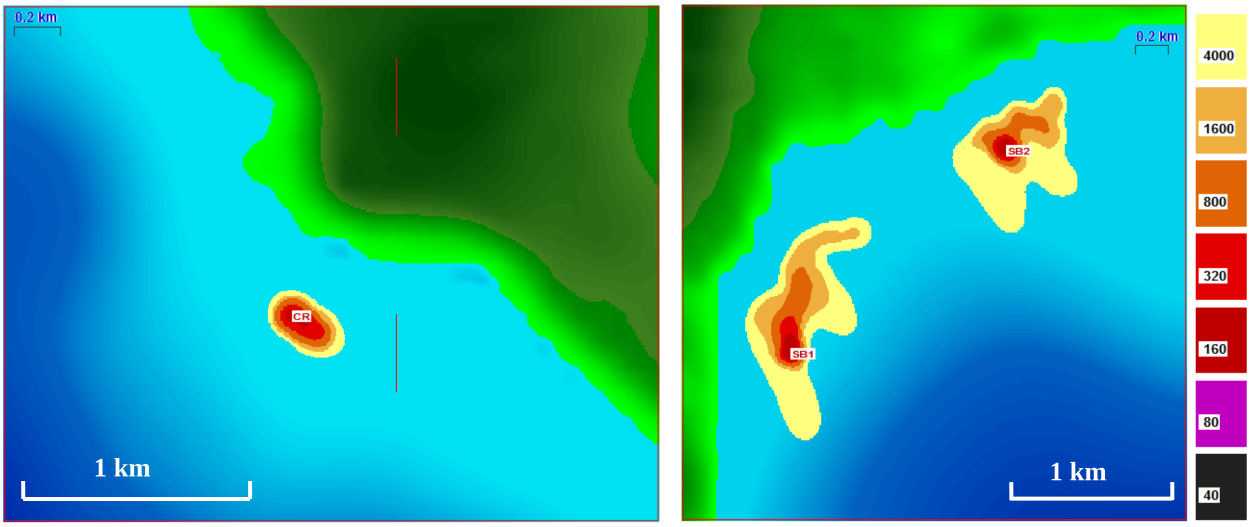

Figure 6. Instantaneous discharge dilution (x:1) at three sites modelled using GCOM3D

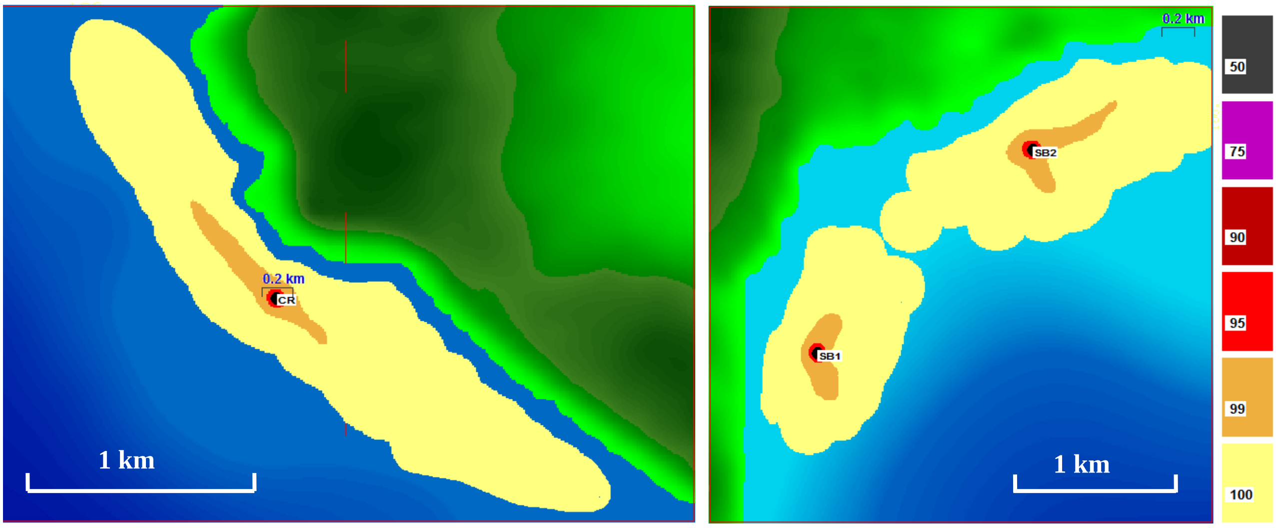

Figure 7. Time averaged plots showing percentage of time complying with a 50:1 mixing requirement at three sites modelled using GCOM3D

CONCLUSIONS

While advances in computer technology have enabled complex modelling and visualisations of seawater desalination plant return flow dispersion, the basis of Australian near-field dispersion modelling remains the empirical dimensionless relationships described by Roberts *et al* (1997) and Nemlioglu and Roberts (2006).

SKM has carried out modelling work with CFD models to fill the gaps of the empirical models, such as multiple nozzle interactions and the impact of currents on mixing zones. Clear limitations were found when applying the CFD model beyond the near field, and consequently caution needs to be applied when modelling mixing using ANSYS FLUENT models in these applications. However, the advantage of being able to model the build up of salinity due to re-entrainment of previously mixed concentrate and to visualise interactions between plumes justifies the use of this tool.

While Australian EPA's have required rapid mixing close to the point of discharge to minimise environmental harm, there has also been interest in the far-field fate of the remaining dense mixed layer. GEMS' GCOM3D has been extensively validated in relation to predicting currents and tidal movements and so allows the transport of the mixed concentrate to be modelled with confidence.

The examples in this paper show that by using a combination of tools the near-, mid-, and far-field, seawater concentrate mixing and transport can be successfully modelled, and recent monitoring results from the Gold Coast desalination plant have validated design modelling work. It is expected that modelling tools will continue to improve to a point where they will match experimental findings, but in the meantime there will still be a need to rely on empirical relationships.

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