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Hindcasts of the fate of desalination brine in large inverse estuaries: Spencer Gulf and Gulf St. Vincent, South Australia

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ABSTRACT

Two major reverse osmosis seawater desalination plants are planned for construction in Spencer Gulf and Gulf St. Vincent, South Australia. A state-of-the-art and carefully calibrated hydrodynamic model (COHERENS) is employed to predict the fate of desalination brine in these sheltered inverse estuaries. In this study, we assume that the brine discharged has a salinity being twice that of ambient gulf water. Findings demonstrate that, owing to slow flushing, the upper reaches of these gulfs are the most unsuitable discharge locations and that, owing to particularly weak neap tides, discharge water can attain high concentrations of >10% (1/10 dilution) and a salinity excess of >5 psu within 100 m distance from the discharge location. Apart from salinity effects, the damage that desalination brine will have on the marine and benthic ecology of South Australian gulfs will crucially depend on the water quality (e.g. levels of dissolved oxygen and other chemicals) of water discharged.

Keywords: Seawater desalination; Brine discharge; Inverse estuary; Hydrodynamic modelling; Flushing time

1. Introduction

Desalination of seawater through reverse osmosis or thermal technology is used in many semi-arid and arid regions in the world as a means to produce high-quality drinking water [1]. This includes the Persian Gulf, the Red Sea, the Mediterranean Sea, and coastal waters of California, Chile and Australia. Downsides of this technology are potential negative impacts on coastal water quality and marine life impaired by concentrate and chemical discharges and air pollutant emissions attributed to the energy demand of the process. In particular, semi-enclosed and shallow seas with abundant marine life can generally be assumed to be more sensitive to desalination plant discharges than exposed, high energy, open-sea locations, which are more capable to dilute and disperse the discharges.

With the worldwide installed capacity for desalination of seawater increasing at a rapid pace [1], there appears to be a trend in Australia to install desalination plants in ecologically more sensitive coastal regions and estuaries. With the Perth desalination plant (using Swan River for intake/discharge) running since 2006, there are plans to build major desalination plants around most other major Australian cities. Two major desalination plants are planned for construction in South Australia, one at Port Stanvac in Gulf St. Vincent for water supply of the Adelaide region, and the other at Point Lowly near Whyalla in upper Spencer Gulf for water supply primarily needed for expanded mining operations by BHP Billiton on the Eyre Peninsula. Spencer Gulf and Gulf St. Vincent, hereafter

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referred to as the gulfs, have a rich and unique biodiversity [2,3]. Dependant on the level of dilution in the ambient sea, discharge of desalination brine including potentially harmful chemicals (e.g., biocides, anti-scalants, antifouling, etc.) can pose a threat to the marine and benthic ecosystem. Recent monitoring of brine discharged by a seawater desalination plant of Alicante (Spain) reported noticeable salinity increases by 0.5 psu above average salinity in the area up to 4 km from the discharge [4].

The aim of this study is to hindcast the fate of desalination brine in South Australian gulfs in terms of hydrodynamic dispersal and dilution of the discharge water. Objectives are to (a) predict far-field concentrations of discharge water on decadal time-scales in conjunction with flushing times of the gulfs, and (b) determine maximum near-field concentrations of discharge water resulting from a lack of tidal mixing during neap tides that are particularly weak in South Australian gulfs.

2. Physical characteristics

2.1. Geography and bathymetry

Spencer Gulf and Gulf St. Vincent are located at a geographical latitude of 35°S (Fig. 1). Spencer Gulf has approximately a triangular shape of 320 km in length, a maximum width of 130 km and an average depth of 24 m. Several smaller islands (Neptune Island, Thistle Island and Gambier Island) are located in the entrance of Spencer Gulf. Gulf St. Vincent is 145 km in length and has an average depth of 21 m. This gulf has two connections to the adjacent shelf. Investigator Strait is bounded by the northern coastline of Kangaroo Island and the south facing coastline of Yorke Peninsula and has an average depth of 34 m. Backstairs Passage is a narrow (13 km wide) opening between Kangaroo Island and the south-western tip of Fleurieu Peninsula and has maximum depths of 35–40 m. The adjacent continental shelf has water depths of 100–150 m.

2.2. Tides

Both gulfs are subject to co-oscillating tides with tidal ranges of ~1 m near the entrance and increasing values toward the head. Upper reaches of Spencer Gulf experience an amplified tidal range of >4 m, whereas a slightly lower tidal range of 3 m is found near the head of Gulf St. Vincent [5]. While tidal currents virtually disappear during neap tides, maximum tidal speeds are moderate (10–50 cm/s) in the gulfs with the exception of Backstairs Passage where peak current speeds of >1 m/s occur during spring tides [6]. The disappearance of tidal flow during neap tides, referred to as dodge tides, is a critical factor for any discharge of pollutants given the lack of tidally induced mixing during these periods lasting 2-3 days.

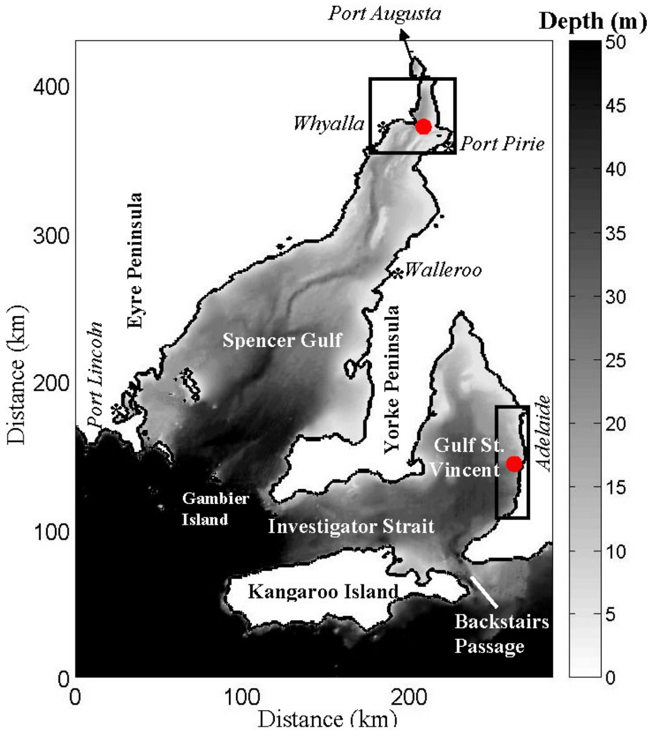

Fig. 1. Far-field study region and bathymetry (m). Dots indicate the locations of planned desalination discharge. Rectangles show sub-domains considered in near-field studies.

2.3. Climate and circulation

The gulfs are situated in a semi-arid climate where annual evaporation exceeds precipitation by far. Observed annual evaporation and precipitation rates at Adelaide airport are 1900 mm/year and 450 mm/year, respectively. Owing to an excess of evaporation over precipitation, the gulfs are classified as inverse estuaries attaining salinities greater than observed in the ambient ocean. Inverse estuaries are characterised by an outflow of dense, saline water in bottom layers which is compensated by inflow of oceanic water in surface layers. In South Australian gulfs, this density-driven circulation is influenced by the earth's rotation, so that bottom-arrested outflows occur along the eastern side of gulfs whereas surface inflows occur along the western sides. This gives rise to an overall clockwise circulation pattern.

The density-driven outflow from Spencer Gulf takes place during austral winter (June–July) and is well documented [7]. Little is known about specific pathways of the outflow from Gulf St. Vincent. During austral summer (January–March), temperature fronts establish across the mouth of Spencer Gulf and in Investigator Strait and Backstairs Passage, significantly reducing the gulf-ocean exchange during this period [8]. A likely generation mechanism of these fronts is summertime upwelling of cold water along the adjacent shelf [9]. It appears that flushing of the gulfs is limited to the winter season during which the outflow of dense, saline water is accompanied by inflow of ambient shelf water of lower salinities. This inflow is the only means of flushing and plays an important role in the gulf's salt budget.

2.4. Planned discharge locations, discharge rates and discharge salinities

There are currently two major desalination plants proposed for the South Australian gulfs region (see Fig. 1). BHP Billiton have proposed to build a desalination plant in upper Spencer Gulf, 15 km north east of Whyalla (Point Lowly) to supply low-salinity water to its Olympic Dam mining operations. The production target is 50 gigalitres/y (~140,000 m^3/d) with approximately the same volume of brine concentrate being discharged into the sea. Brine will be released locally via multiple point sources at a depth of 20 m, which is close to the maximum depth found in this part of the gulf. The other desalination plant, proposed by the South Australian Government, is planned to be installed on a former Port Stanvac oil refinery site, 20 km south of Adelaide's centre. The initial production target of 50 gigalitres/y is similar to that in upper Spencer Gulf with a possible doubling of the production capacity in the near future. Again, brine will be discharged at a water depth of around 20 m. In contrast to upper Spencer Gulf, this discharge will take place on a sloping seafloor that gradually deepens to >30 m with increasing offshore distance.

Without further treatment, the salinity of discharge brine will be about twice that of the intake water [1], which is assumed in this work. Nevertheless, for the Gulf St. Vincent plant, there are indications that salinity levels will be reduced to some (yet unknown) degree via pre-dilution of the brine concentrate with lower-salinity water from a nearby wastewater treatment plant. An assessment of marine impacts of this method remains for future studies.

3. Methodology

3.1. Hydrodynamic model

This study employs the hydrodynamic model COHERENS (COupled Hydrodynamic Ecological model for REgioNal Shelf seas) [10] that has been successfully applied by the research group of the leading author to the Persian Gulf [11,12] and Bass Strait [13]. This model is based on conservation principles for momentum, mass and energy for an incompressible fluid on the f-plane (constant geographical latitude) and is formulated in terrain-following sigma coordinates. The model is driven by prescription of meteorological forcing fields used to predict residual fluxes of heat, fresh water and momentum at the air–sea interface. Tides are created via prescription of sea level variations at open lateral boundaries. The model includes a variety of schemes for the parameterization of sub-grid scale processes. Bottom friction is described by means of a quadratic bottom-friction law and prescription of a certain bottom roughness length. COHERENS is employed in its standard configuration [see 10].

3.2. Far-field study

3.2.1. Bathymetry

The model bathymetry is based on a data set provided by Geoscience Australia at a spatial resolution of 1/100 degree. These data do not resolve the narrowest sections of upper Spencer Gulf within 10 km distance from Port Augusta. Our model domain does not include this section. Far-field experiments encompassing both gulfs use a coarser version of this bathymetry with 3/100 degree resolution (Δx = 2.73 km in the zonal direction and Δy = 3.33 km in the meridional direction) and 10 equidistant vertical sigma levels. A diffusion-based smoothing algorithm is used to eliminate sharp steps in bathymetry. Minimum water depth is set to 5 m (the model does not allow for grid cells to fall dry) and the maximum water depth on the adjacent shelf is constrained to 150 m.

3.2.2. Initial and boundary conditions

Tidal sea-level boundary forcing is implemented at the western and eastern open boundaries of the model domain using amplitudes and phases of the four dominant tidal constituents (M_2, S_2, O_1 and K_1) provided by the National Tidal Centre of the Bureau of Meteorology, Australia. For simplicity, tidal forcing data are prescribed spatially uniform along the respective boundary. Reasonably accurate tidal results (see below) were achieved with a spatially uniform bottom roughness length of 5 mm. Zero-gradient conditions are used for sea levels along the southern boundary.

The model domain is initialized with a uniform temperature of 16.0°C and a salinity of 35.75 psu with simulations commencing in late winter (August). Salinity of shelf water does not vary significantly (compared to that of the gulf) and is kept at a boundary value of 35.75 psu throughout the simulation. Influences of the ambient shelf are described in the model via prescription of monthly mean boundary temperatures extracted from the South East Fishery (SEF) ocean movies [14]. During austral summer (January–April), boundary-temperature forcing is expanded to all shelf areas exceeding a depth of 50 m to mimic the effect of coastal upwelling, which cannot be simulated in conjunction with prescribed tidal boundary forcing. This form of data assimilation is done via a Rayleigh damping term with a time-adjustment factor of 5 days.

Monthly mean climatological data from the NCEP reanalysis grid for the period 1978–998 was used to force the model. These data include air temperature, wind speed and direction, relative humidity, cloud cover and precipitation. Two different time series were available: one being centered at −33°S and the other at −35°S. The average of both time series is taken as being representative for both gulfs. Relative humidity data supplied by NCEP appeared unreliable and were replaced by climatological data for Adelaide Airport provided by the Bureau of Meteorology, Australia. Conventional heat-flux formulae, detailed in [10], are used to calculate residual heat fluxes and evaporation-caused salinity changes.

3.2.3. Implementation of brine discharges

Brine release is implemented in the model code as a point source via the flux condition:

$$\frac{\partial S}{\partial t} = \left(S_{\text{brine}} - S\right)\frac{q_{\text{brine}}}{V} \tag{1}$$

where S is the salinity in the grid cell containing the discharge outlet, t is time, S_{brine} is the salinity of the brine, q_{brine} is the discharge rate and V is the volume of the respective grid cell. In the far-field study, brine is released in the bottom-nearest grid cell at a total water depth >20 m at two distinct locations (see Fig. 1). The thickness of this cell is 2 m. Salinity of the brine is assumed at S_{brine} = 80 psu, which is approximately twice the salinity of gulf water. The discharge rate is set to q_{brine} = 1.6 m^3/s being equivalent to a discharge of 50 gigalitres/y. Brine discharge is "switched on" after the initial 2 years of simulation. It should be emphasized that, owing to relatively coarse grid spacing, the brine is already substantially diluted with ambient water as it enters the grid volume. The temperature of the brine discharge is assumed to be the same as that in ambient water. Net flow introduced by the discharge of $q_{\text{brine}}/V \approx 1\times10^{-3}$ mm/s is negligibly small and therefore neglected.

In order to derive three-dimensional concentration distributions of brine discharge water, we initialise an independent Eulerian concentration field C with zero values and describe a point source at the discharge sites by means of:

$$\frac{\partial C}{\partial t} = \left(100\% - C\right)\frac{q_{brine}}{V} \tag{2}$$

This tracer field is subject to both currents (advection) and mixing (diffusion). The model simulation returns a concentration distribution (in units of per cent) which is useful to derive distributions of any (conservative) dissolved pollutant contained in the brine.

3.2.4. Calculation of flushing times

Flushing time is defined as the time it takes to replace the volume of a semi-enclosed sea or estuary with water from the ambient ocean. A conventional approach to calculate flushing times is to initialize a certain part of the model domain with an Eulerian tracer concentration field of 100% value while allocating zero values to remainder parts of the domain. Flushing time is then calculated as the time it takes for this concentration to drop below a threshold value of $1/e$ (36.8%). This approach gives a spatial distribution of flushing times [see 11], but results depend on the definition of the threshold value.

In this study we employ a similar but more robust method to calculate flushing times. This method does not require specification of a threshold value and is based on the "age" of gulf water with reference to an ambient ocean of zero age. Again, a field of Eulerian tracer concentration, called water age A, is used with initial zero values everywhere in the model domain. From 2 years of simulation onward, water inside the gulfs are allowed to age according to the equation [13]:

$$\frac{\partial A}{\partial t} + \text{Advection}(A) = \text{Diffusion}(A) + 1 \tag{3}$$

This advection–diffusion equation contains an additional term (unity) on the right-hand side which implies that the water age increases linearly with time in the absence of advection and diffusion. Nevertheless, owing to exchange with the ambient ocean of zero age, advection/diffusion will always limit the maximum age for a semi-enclosed gulf. The resultant age values can be directly taken as a proxy of flushing time [13].

3.2.5. Total simulation time and data output

Commencing in August, the coarse-resolution model is run for a total of 7 years with a time step of Δt = 30 s. Robust seasonal cycles of temperature and salinity distributions in the gulfs develop within the initial 2 years of simulation. Harmonic analysis of tidal currents is performed from day 60 over the following 60 days of the simulation. In addition to this, outputs consist of monthly mean distributions of all variables. Graphs were produced with Matlab.

3.3. Near-field studies

Near-field studies are conducted at a spatial resolution of 1/50 degree (455 m in the zonal direction and 555 m in the meridional direction) in selected sub-domains containing the two discharge sites (see Fig. 1). To this end, the Geoscience Australia bathymetry has been interpolated onto a finer grid and a diffusion algorithm has been applied for smoothing purposes. Near-field studies employ 20 vertical sigma levels. The vertical spacing of the lower 10 sigma levels is set to 20 cm. The remaining 10 sigma levels are evenly spread over the remainder of the water column. Using Eq. (1), desalination brine is released evenly over the lowermost 1 m of the water column. The near-field simulations are forced entirely via tidal boundary forcing predicted by the far-field study. Wind stresses and other air-sea fluxes are ignored and temperature and salinity are assumed uniform throughout the model domain. Total simulation times are 100 days.

4. Results and discussion

4.1. Far-field study

4.1.1. Tides

Compared with observations [15], tidal amplitudes of individual tidal constituents are slightly overestimated in Gulf St. Vincent and slightly underestimated in Spencer Gulf (Fig. 2a). Associated relative errors are <10% in most locations and the RMS-error of the regression is relatively small (0.55 cm). Tidal phases are realistic in both gulfs (Fig. 2b). Given the coarse spatial resolution of this far-field study, we regard the simulated tidal response of the gulfs as accurate enough in the context of this study.

4.1.2. Seasonal temperature and salinity variations

Compared with observations [16], seasonal cycles of temperature and salinity are predicted reasonably well in Spencer Gulf in terms of both absolute values and ranges (Fig. 3). The model appears to slightly overestimate summer temperatures in certain regions by up to 1ºC. Note that the model domain does not include the narrowest northern reaches of Spencer Gulf within 10 km distance from Port Augusta where salinities peak at values of 49 in summer.

Seasonal variations of temperature and salinity in Gulf St. Vincent are not well documented. However, the model predictions agree with the sparse data available [17–19] (Fig. 4). Note that there are only few observations taken near the head of this gulf, where the model predicts summer salinities of up to 42. On the basis of these predictions, the authors conclude that the model is capable to simulate seasonal variations of temperature and salinity in both gulfs reasonably well.

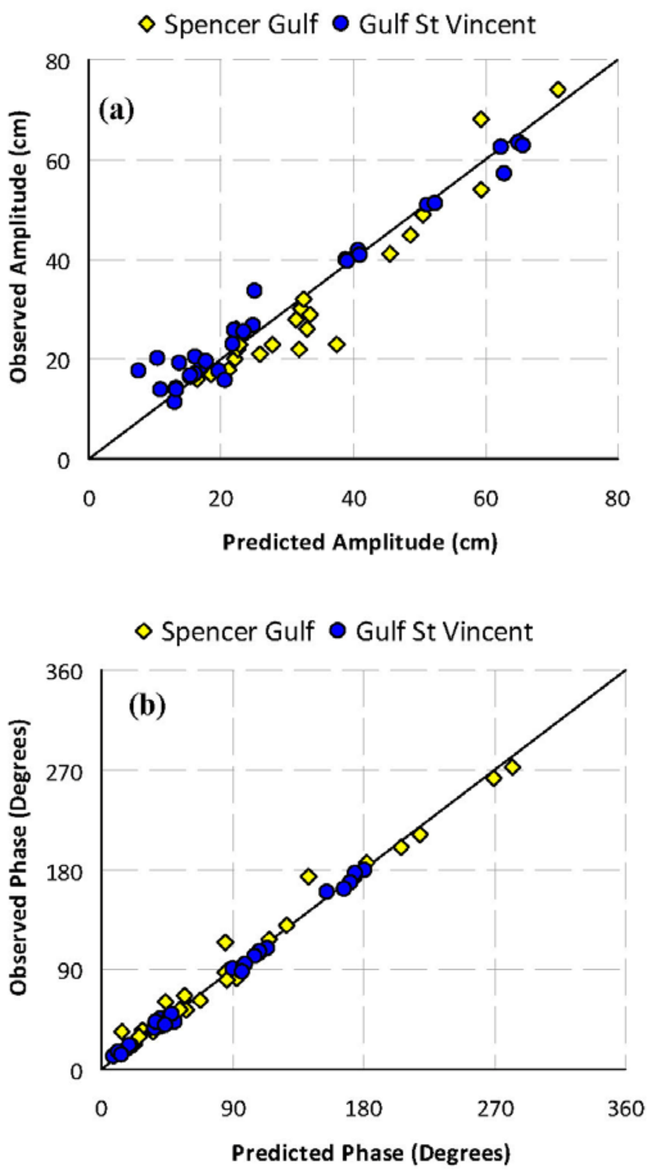

Fig. 2. Far-field study. Comparison between simulated with observed values of (a) tidal amplitudes and (b) tidal phases for the four tidal constituents (M2, S2, O1, S1). Observations are taken from Easton [20].

It should be emphasized that lateral density gradients, which are the main driver of the gulfs' circulation, are maximum during the winter months, whereas these almost disappear in lower portions of both gulfs during summer.

4.1.3. Winter and summer aspects of the gulfs circulation

The model accurately reproduces the density-driven winter outflow from Spencer Gulf (Fig. 5) in agreement with observational evidence [7]. There are no direct observations of the outflows from Gulf St. Vincent. The model predicts two branches of this outflow, one leaving

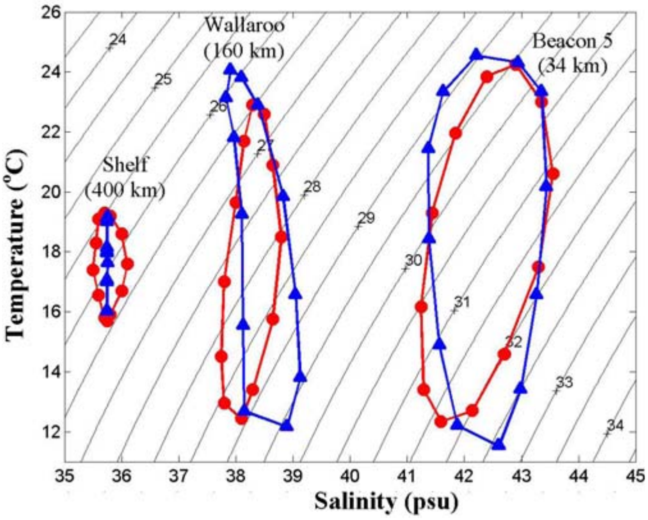

Fig. 3. Far-field study. Simulated monthly mean (triangles) and observed (full circles) values of temperature and salinity at selected locations in Spencer Gulf. Contour lines refer to true density minus 1000 kg/m^3. Distances are given with respect to Port Augusta. Observations are taken from Nunes and Lennon [21].

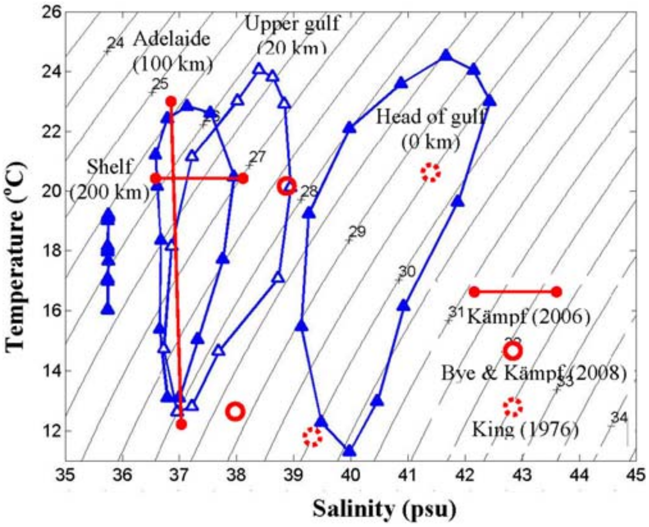

Fig. 4. Far-field study. Simulated monthly mean (triangles) and observed (circles) values of temperature and salinity at selected locations in Gulf St. Vincent. Lines indicate observed ranges. Contour lines refer to true density minus 1000 kg/m^3. Distances are given with respect to the head of gulf.

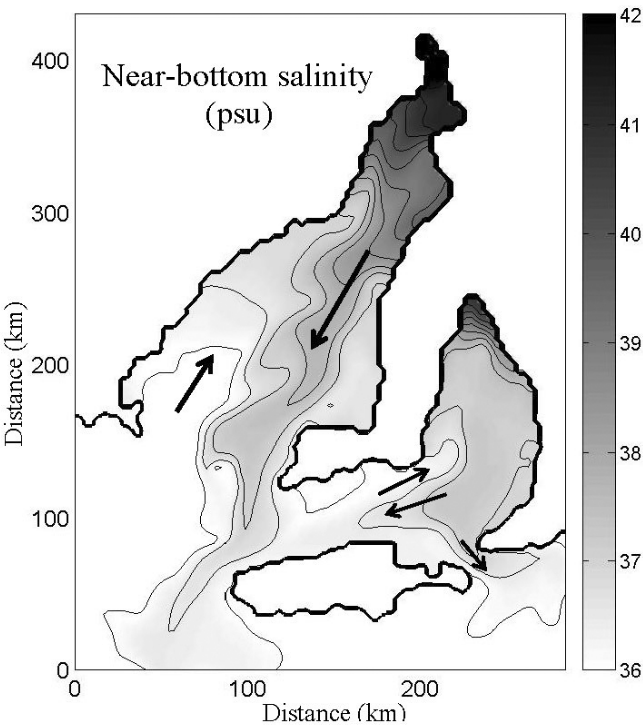

Fig. 5. Far-field study. Simulated distribution of near-bottom salinity for austral winter. Arrows indicate flow directions.

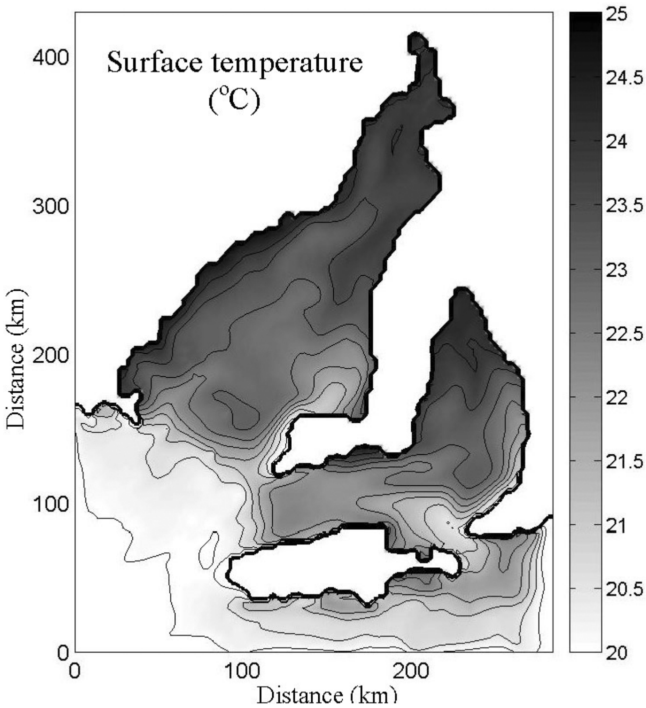

Fig. 6. Far-field study. Simulated distribution of surface temperature (°C) for austral summer.

the gulf through Investigator Strait and the other one through Backstairs Passage. During this period, new shelf water enters both gulfs along their western sides, in agreement with field observations [7,17].

In summer, when then density forcing almost disappears in lower portions of the gulfs, there is only little exchange between the gulfs with the ambient shelf water and temperature fronts establish across the entrances of

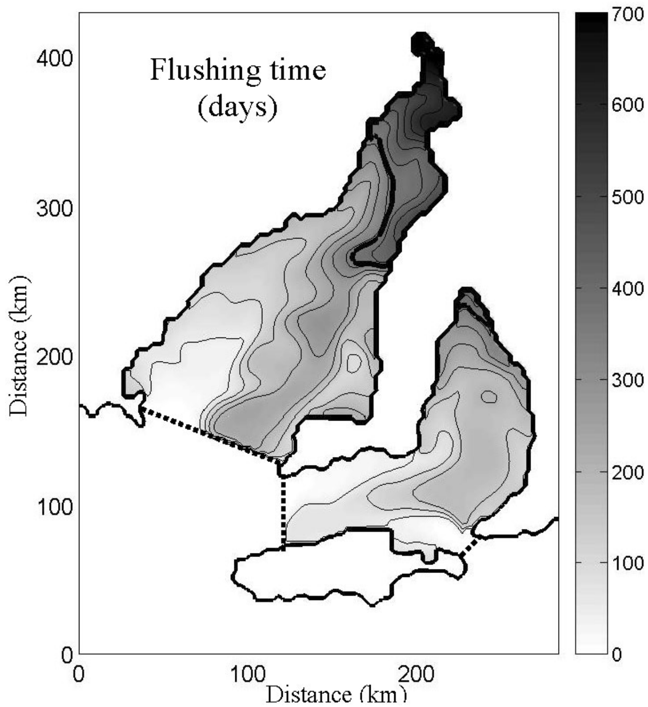

Fig. 7. Far-field study. Simulated distribution of flushing time (days) for austral winter. Thick lines highlight a flushing time of one year. Dotted lines are the assumed boundaries between gulf and shelf water used for the flushing time calculations.

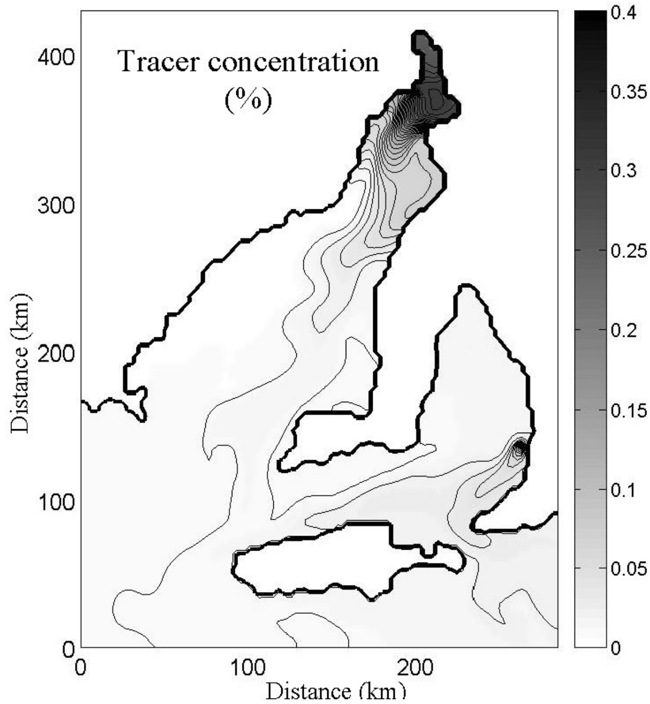

Fig. 8. Far-field study. Simulated distribution of concentration of discharge water (%) for austral winter.

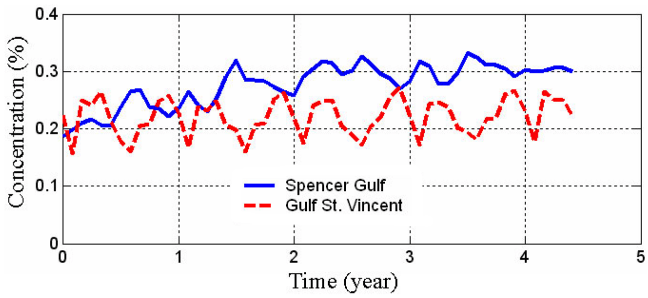

Fig. 9. Far-field study. Simulated evolution of concentration of discharge water (%) at the discharge sites in Spencer Gulf and Gulf St. Vincent (locations are shown in Fig. 1).

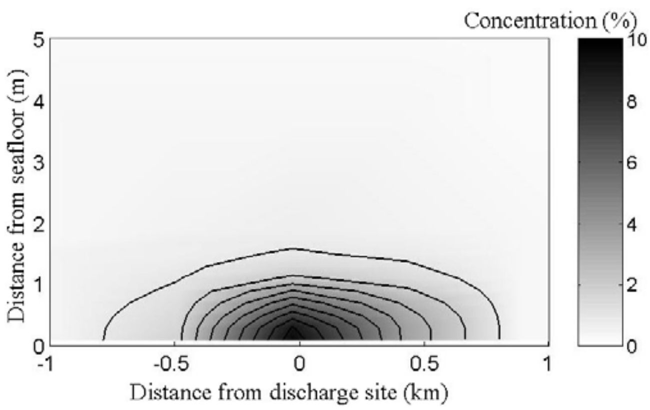

Fig. 10. Snapshot of the concentration of discharge water (%) in vicinity of the Spencer Gulf discharge site.

Spencer Gulf and Investigator Strait (Fig. 6) in agreement with observations [8]. The model predicts a zone of relatively low surface temperatures in Backstairs Passage created via strong tidal mixing. This zone can be identified in satellite-based data [see 9].

4.1.4. Flushing times and dispersal of brine discharge

Owing to the density-driven exchange circulation during winter, lower portions of the gulfs are flushed on an annual basis with flushing times of <6 months (Fig. 7). In contrast to this, the upper portions of the gulfs cannot be flushed annually. Upper Spencer Gulf (north of Walleroo) attains flushing times between 1 and 2 years. Water near the head of Gulf St. Vincent attains flushing times of 1 year. Hence, the desalination plant in upper Spencer Gulf is located in a remote region of extremely long flushing. In terms of flushing, upper Spencer Gulf is the most unsuitable location of pollutant discharges of any kind. On the other hand, the Port Stanvac desalination plant in Gulf St. Vincent is situated in a relatively better flushed environment with flushing times of 3–6 months.

Giving the slow flushing in upper Spencer Gulf, discharge water accumulates in the far field at concentrations of 0.3% within 20 km distance from the discharge site (Fig. 8). Far-field concentrations of discharge water in

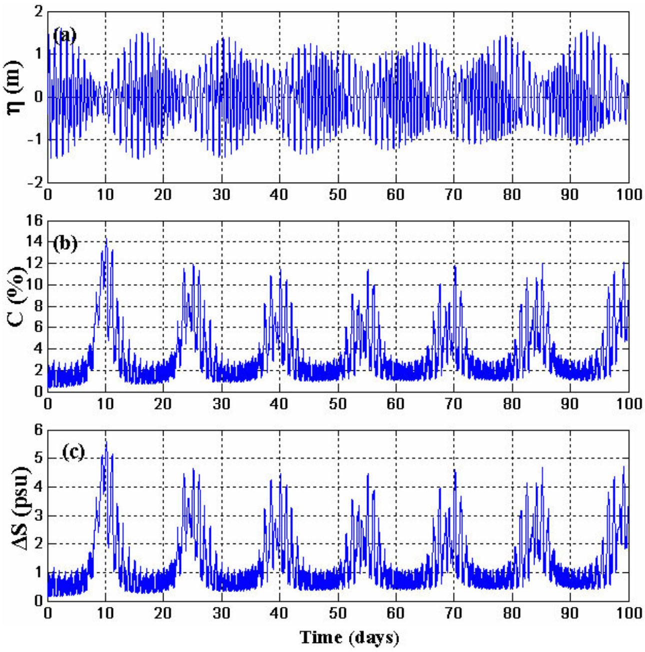

Fig. 11. Near-field study. Evolutions of (a) sea level (m), (b) concentration of discharge water (%), and (c) salinity excess at the Spencer Gulf discharge site.

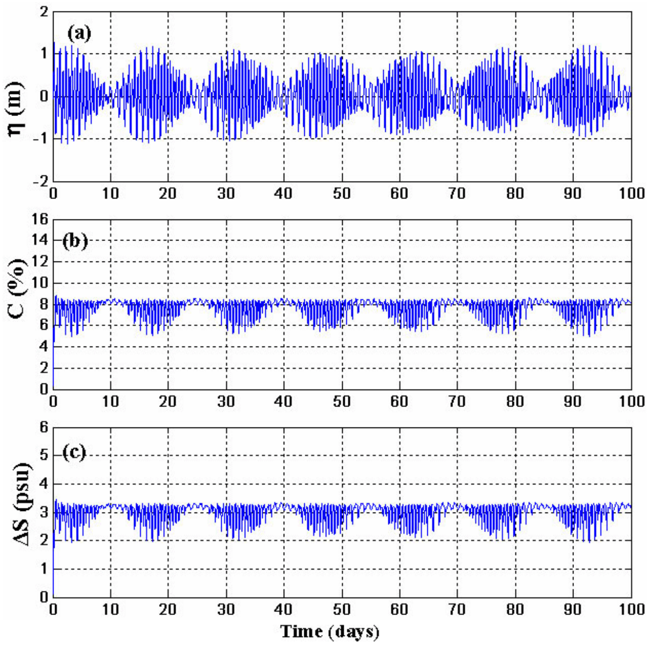

Fig. 12. Near-field study. Evolutions of (a) sea level (m) (b) concentration of discharge water (%), and (c) salinity excess at the Gulf St. Vincent discharge site.

Gulf St. Vincent are much smaller than in Spencer Gulf with values of <0.1%. Concentrations of discharge water near the discharge locations are relatively steady on annual time scales (Fig. 9). Variations of <30% are caused by seasonal changes of the circulation patterns and variations of the magnitude of the wind stress. Nevertheless, these apparently low concentrations are implied by the coarse grid spacing chosen in the far-field study. With a finer grid spacing, resultant concentrations increase by >1 order of magnitude in the near field.

4.2. Near-field studies

The near-field studies reveal that the discharge water attains high concentrations >5% within 500 m distance from the discharge site in upper Spencer Gulf (Fig. 10), where the tidal range is ~3 m. A closer analysis reveals that peak concentrations are ~2% during spring tides, but they increase locally to values of 12% during dodge tides (Fig. 11). Associated salinity increases are <1 ppt during spring tides and up to 4 ppt during dodge tides. Experiments (not shown) using an even finer spatial resolution of 100 m indicate that peak concentrations within 500 m from the discharge can increase to values >20% during dodge tides, being associated with local salinity increases by up to 10 psu. This demonstrates that the absence of tidal mixing during dodge tides can lead to high transient salinity and pollutant loads in the near field.

The tidal range at the discharge site in Gulf St. Vincent is slightly smaller (~2 m) compared with that in upper Spencer Gulf. Peak tidal currents are weaker here and we expect comparatively less dilution. Indeed, peak concentrations of discharge water and associated salinity anomalies during spring tides attain higher values of 8% and 3 ppt, respectively, for the Gulf St. Vincent discharge, but a markedly increase in concentrations during dodge tides does not occur (Fig. 12). Instead of this, peak concentrations remain steady over the neap-spring tidal cycle.

A first analysis indicates that peak concentrations of discharge water are influenced by (a) the shape of the local bathymetry during dodge tides and (b) the magnitude of the tidal range during spring tides. A closer study of this tidal-bathymetric modulation of dilution near the discharge location remains for the future.

5. Conclusions

A carefully calibrated three-dimensional hydrodynamic model (COHERENS) was applied to hindcast the planned discharges of desalination brine in South Australian inverse estuaries, Spencer Gulf and Gulf St. Vincent.

The far-field study revealed that, owing to slow flushing (>1 year), the upper reaches of the gulfs are the most unsuitable locations for brine discharge. Studies indicate that brine discharge in upper Spencer Gulf leads to long-term accumulation of discharge water at steady concentrations of 0.3% in the far field (within 20 km from the discharge site). Although this concentration seems relatively low, long-term exposure and potential accumulation of pollutants in bed sediment is of ecological concern.

Near-field studies revealed that dilution of discharge water can substantially weaken in the absence of tidal mixing during dodge tides (which are extremely weak neap tides in these gulfs). In upper Spencer Gulf, the concentration of discharge water might increase during dodge tides to values >12% with associated salinity changes of >5 psu. These calm periods of 2–3 days in duration occur roughly every 2 weeks and are particularly critical in terms of marine impacts. Interestingly, a decrease in dilution during dodge tides was not predicted for the planned brine discharge of Adelaide in Gulf St. Vincent. Here, peak concentrations remained relatively steady during the spring-neap tidal cycle at values of 8% and salinity increases of 3 psu. This suggests that some discharge locations are more sensitive to dodge tides than others, an interesting feature that remains for thorough exploration in the future.

In agreement with many previous studies [e.g. 1,4], the conclusion of this study is that the choice of location is crucial to minimize marine impacts of seawater desalination. Owing to a sheltered nature and associated slow flushing and given that the marine ecosystems in adjacent marine regions are already under stress [22,23], discharge of desalination brine into South Australian gulfs might have severe and irreversible negative impacts on the marine and benthic environments.

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