APPENDIX O9

Salinity of Upper Spencer Gulf

O9 SALINITY OF UPPER SPENCER GULF

An understanding of the natural salinity range at Point Lowly is critical to the interpretation of the hydrodynamic modelling and ecotoxicology results, and the assessment of impacts of the proposed desalination plant. The accurate measurement of salinity is therefore critical to the assessment.

O9.1 MEASUREMENT OF SALINITY

O9.1.1 Introduction

Absolute salinity is defined as the mass fraction of dissolved material (including gases) in seawater (Millero et al. 2008), and can be expressed in units such as parts per thousand or g/L. This dissolved material comprises mainly sodium and chloride ions (the constituents of common salt). Other major components are magnesium, calcium, potassium, sulphate and bicarbonate ions, and there are many tens of trace elements (Turekian 1968; Drever 1982). There is little variation in the composition of seawater (i.e. the ratio of the various ions) across the world's seas or between oceanic and estuarine waters, with the variation in absolute salinity measurements being approximately 0.03 g/L (Millero et al. 2008)[3].

The amount of dissolved material is considered to be almost impossible to measure in practice (Millero et al. 2008). Less direct methods are therefore commonly used but results using different methods are often inconsistent. Consequently, the measurement of salinity needs to be thoroughly understood prior to undertaking analysis of salinity trends.

Methods for measuring salinity include:

- electrical conductivity – based on the principle that the major constituents of salt are conductive ions
- evaporation – the solvent is evaporated (as are dissolved gases) and the residual solids weighed
- refraction – based on the principle that the refractive index of light is related to the concentration of solids in the water
- summation of ions – the mass of the major constituent ions are determined analytically and summed
- density – uses the seawater equation of state (UNESCO 1981) which links density and salinity for a known pressure and temperature.

The standard against which salinity is compared and instruments are calibrated is the Practical Salinity Scale (PSS-78), introduced in 1978 (UNESCO 1981), and based on electrical conductivity. This scale defines salinity in terms of a ratio of conductivity of the sample to that of a standardised solution with a particular composition (pure potassium chloride) and at a particular temperature and pressure. The result is a unitless salinity measure considered to be approximately 0.5% below the absolute salinity in g/L (i.e. 0.2 based on an absolute salinity of 40 g/L).

O9.1.2 Background to measurement anomalies

Equations and constants for computing salinities up to 42 g/L from in-situ measurements of conductivity (and temperature and pressure) were provided as part of PSS-78 (Fofonoff and Millard 1983). Poisson and Gadhoumi (1993) published further equations applicable for salinities up to 50 g/L. Other algorithms have been developed by the Australian Water Quality Centre (AWQC, unpublished data) and the Environmental Protection Authority (Duncan et al. 2007). The difference between salinities calculated using the PSS-78 and AWQC equations, however, is up to 0.2 g/L for salinities typical of Point Lowly, 0.5 g/L for salinities typical of Port Augusta (48 g/L) and 3.5 g/L for reverse osmosis return water (75 g/L). These differences are doubled for the comparison between the PSS-78 and EPA equations (See Figure O9.1).

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[3] Estimated from the density difference of 24 g/m^3

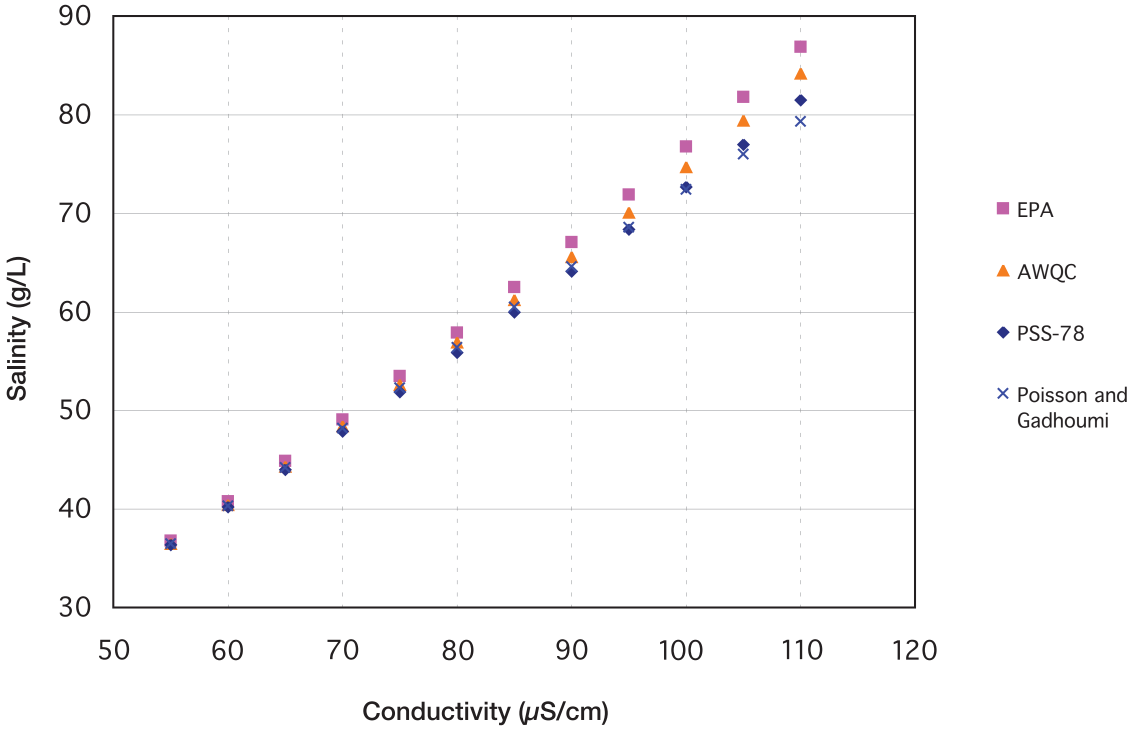

Figure O9.1 A comparison of conductivity to salinity conversion algorithms

O9.1.3 Comparison of methods using Upper Spencer Gulf seawater

The salinity of 10 seawater samples from Point Lowly and Port Augusta was measured using a variety of methods (see Table O9.1).

Table O9.1 Methods used for measuring salinity

Method / instrument	Tester / laboratory	Notes
Estimation from density	Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami	The RSMAS has been the source of some of the most significant publications on the measurement of salinity (e.g. Millero 2000, Millero et al. 2008) and as such is highly credible
Autolab Salinometer (conductivity based)	Dr Richard Nunes-Vaz (consultant oceanographer) using laboratory at Flinders University (see Plate O9.1)	The instrument was calibrated with standard seawater, and samples were diluted to a salinity within its operating range. The method is described in more detail in Appendix O9.4. This is the same instrument and method that was used to analyse samples in the 1980s (Nunes and Lennon 1986). This data has been used to calibrate the hydrodynamic model (see Appendix O11.2)
Radiometer CDM92 conductivity meter	Australian Water Quality Centre (AWQC)	Uses a CDC866T 4-pole conductivity electrode
Conductivity using YSI meter	Geotechnical Services (ecotoxicology laboratory)	
Data logger – conductivity based YSI 6600 EDS Sonde	Water Data Services	
Evaporation	AWQC	Dried at 180 °C using Standard Method 2540C (APHA et al. 1995)
Evaporation	Geotechnical Services (ecotoxicology laboratory)	As above
Summation of ions	AWQC	
Portable refractometer	Flinders Power	
Refractometer	Geotechnical Services (ecotoxicology laboratory)	

Comparisons of the different measurement methods across the samples showed a number of patterns (see Figure O9.2):

- The results using the estimation from density and salinometer methods were within 0.1 g/L (average 0.05 g/L); duplicates of samples varied by a similar amount for both methods.
- The results for each sample ranged over 6 g/L, with the methods in order from highest to lowest salinity being evaporation, portable refractometer, summation of ions, salinometer/estimation from density, and other conductivity based measurements. Other samples, however, have produced measurements based on conductivity that are similar to those based on summation of ions (see Appendix O9.2).
- Although the rank order of the methods was consistent across samples, the relative differences between the estimation from density and the other methods was not (see Figure O9.3, Table O9.2). Apart from the salinometer, the summation of ions and evaporation methods were the most consistent, within a range of approximately 1 g/L (0.3-1.4 g/L and 2.7-3.7 g/L respectively).

Table O9.2 Differences in salinity measurements compared with density based measurement

	Min	Max	Range	Mean	Standard deviation
Evaporation	2.72	3.72	0.99	3.20	0.31
Portable refractometer	0.02	3.48	3.47	2.13	1.50
Summation of ions	0.34	1.41	1.07	0.94	0.38
Salinometer	-0.01	0.11	0.12	0.05	0.04
Other conductivity	-2.99	-1.18	1.81	-2.13	0.51

The two methods that gave the most consistently similar results for samples from Upper Spencer Gulf were laboratory based measurement of salinity using an appropriately calibrated salinometer (see Appendix O9.4 and Plate O9.1) and accurate measurement of density.

Plate O9.1 Salinity measurement using salinometer

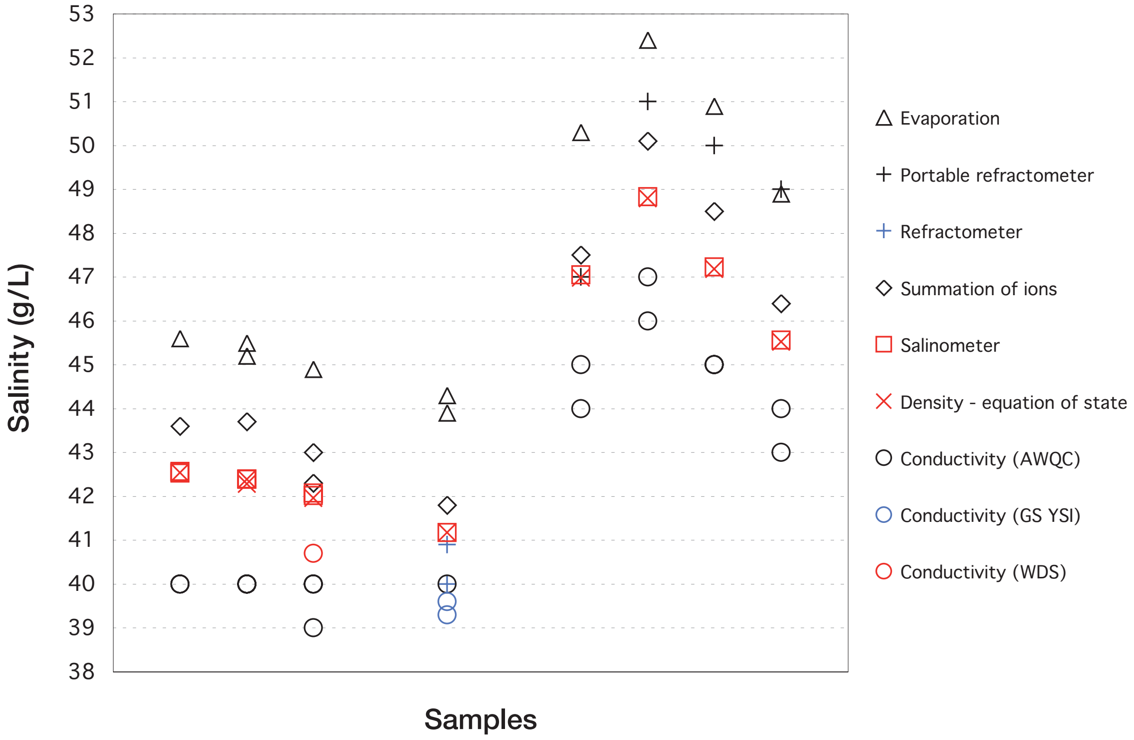

Figure O9.2 Comparison of salinities measured using different methods

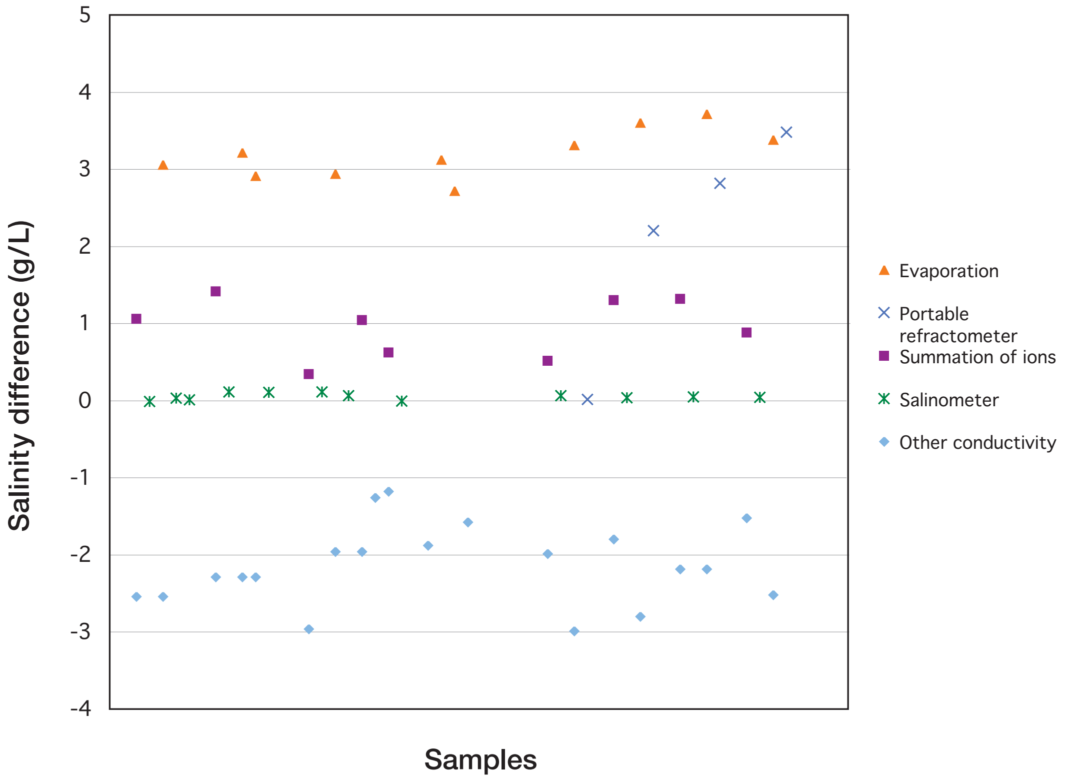

Figure O9.3 Differences in salinity measurements compared with density based measurement

There are a number of possible reasons for the measurement anomalies, as follows:

- Conductivity instruments are generally designed to measure salinity within the range of normal seawater (35–36 g/L). At the salinity prevailing in Upper Spencer Gulf (40–43 g/L), conductivity instruments may be near or beyond their upper limit of accurate measurement. Dilution of samples prior to measurement and subsequent correction is a possible solution
- Some instruments are incapable of providing highly accurate outputs (e.g. portable refractometer)
- Other possible sources of anomalies include incorrect calibration of instruments, operator error and sample contamination

O9.2 REVIEW OF SALINITY RECORDS NEAR POINT LOWLY

Most measurements of salinity near Point Lowly were made three decades ago or in the past few years (see Table O9.3). The comparison of measurement methods (Appendix O9.1) shows that the use of a laboratory based salinometer remains the most accurate method for measuring salinity. The instrument requires careful calibration, and dilution of the sample for salinities higher than 42 g/L, which is the upper limit of the Practical Salinity Scale (UNESCO 1981). Operation of this instrument by Dr Richard Nunes-Vaz (during 1982-1985 and 2008) is described in Appendix O9.3. Although the Department of Fisheries and CSIRO used salinometer, calibration details are not available (Johnson 1981; Corlis et al. 2003).

The measurements by Dr Nunes-Vaz, showing a range across all seasons from 40–42 g/L (Nunes & Lennon 1986) and some measurement of 42.5 g/L in April 2008, can therefore be regarded with the highest level of confidence. A high level of confidence can also be placed on other measurements using a salinometer. However, the measurement of 44.8 g/L on one occasion by the Department of Fisheries and the single measurement of 44.1 g/L by CSIRO do appear to be erroneous (R Nunes-Vaz, Consultant Oceanographer, pers. comm., 28 August 2008). Excluding these measurements, the range is 40–43 g/L.

The remaining measurements are conductivity based field or data logger measurements, and cannot be regarded with a high level of confidence. This is underlined by discrepancies of up to 2.3 g/L between salinities based on conductivities measured by a Troll 9500 water quality meter and those measured by AWQC. It is likely that the conductivities as measured by AWQC and the data loggers understate the salinity, but measurements made using the Yeo-Kal meter for field measurements (Water Technology 2005, GHD 2008) may overstate the salinity. Their similarity to salinities based on summation of ions, which has been shown to overstate salinity (see Appendix O9.1), are further evidence of this.

The salinity range at Point Lowly, based on the most reliable measurements, is most likely to be 40–42.5 g/L, although there is some credible evidence that it may extend to 43 g/L.

Table O9.3 Salinity measurements near Point Lowly

Organisation	Sampling period	Reference	Number of measurements	Salinity range (g/L)	Details
Department of Fisheries	1974-1978, all seasons	Johnson 1979, 1981	24+10, some possible overlap	40-43, one reading of 44.8	Autolab conductivity salinity-temperature meter (+/- 0.1 g/L)
Flinders University (Dr Richard Nunes-Vaz)	1982-1985, all seasons	Nunes 1985; Nunes & Lennon 1986; Nunes & Lennon 1987, Nunes-Vaz et al. 1990	13	40-42	Autolab salinometer
CSIRO	February and June, 1991	Corlis et al. 1993	2	Single measurements of 44.1 and 41 respectively	Autolab Inductively Coupled Salinometer (Model 601-MIII)
Water Technology Pty Ltd	July 2005	Water Technology 2005	8	42.3-42.9	Yeo-Kal multi-probe water sampler
University of Adelaide	July and August 2007	B Gillanders, University of Adelaide, pers. comm., 3 December 2008	14	38.6-39.4	A YSI 6600 Multi-parameter Water Quality Meter (CTD sonde)
Dr Richard Nunes-Vaz (for BHP Billiton)	2008, April, June, July, August	Unpublished (some results in Appendix O9.4)	6	41.2-42.5	Flinders University Salinometer
BMT WBM Pty Ltd (for BHP Billiton)	December 2007 to January 2008	Unpublished	Continuous	40.6 maximum	Greenspan Model CS304 water quality probe
Arup (for BHP Billiton) using AWQC laboratory	December 2006 to April 2007	GHD 2008	7	Conductivity based: 39-41 Summation of ions: 40.2-42.6	Radiometer CDM92 conductivity meter
Wata Data Services (for BHP Billiton)	Continuous since May 2007	Unpublished	Continuous	Maximum value 42.4, 99th percentile 41.7	A YSI 6600 Multi-parameter Water Quality Meter (CTD sonde)
GHD (for BHP Billiton) using various laboratories	Monthly from September 2007 to June 2008	GHD 2008	7	Conductivity based: 38.9-44 Summation of ions: 41.1-45.1	Variety of meters used to measure conductivity (Troll 9500, Horiba, Yeo-Kal 611)

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APPENDIX O9.4

The long-term salinity of Upper Spencer Gulf (report by Dr Richard Nunes-Vaz, 2008)

See overleaf for report.

The Long-Term Salinity of Upper Spencer Gulf

Dr Richard Nunes-Vaz

August 2008

Summary

Questions have been raised about the long-term salt balance of Spencer Gulf (particularly Upper Spencer Gulf, north of Point Lowly) and whether salinities have already, or are likely to change in response to a shift towards hotter, dryer climatic conditions associated with global warming. The question is relevant to environmental assessment of a proposed desalination plant in Spencer Gulf for two reasons. Firstly, it defines the context or baseline within which desalination occurs, whether the baseline itself is changing significantly, and whether the Gulf is (or may become) salinity-stressed to a point at which desalination could tip a delicate environmental balance in the wrong direction. Secondly, it provides a metric for making worst case assessments of the probable long-term impact of desalination on Gulf salinities.

To assess long-term salinity trends, the ‘salt loading’ (total mass of salt) in Upper Spencer Gulf was measured in August 2008, and compared with similar assessments from numerous salinity surveys conducted (by the same author) in the mid 1980s. Salt loading demonstrates an annual cycle that reflects the net influences of fluid gain and loss (due to evaporation, rainfall and runoff) and mixing with the less saline waters further south. With regard to overall salt loadings, fluid loss due to evaporation can be considered equivalent (in behaviour, but not in magnitude) to desalination.

Results indicated that the current salt loading of Upper Spencer Gulf lies within the bounds of measurements made a quarter of a century earlier, and has therefore not changed significantly, despite broad indications of higher temperatures, higher evaporation rates and lower rainfall over the same period. Gulf salinities therefore appear to be robust to environmental factors that far surpass the potential large-scale influences of proposed desalination, and there is no indication that a significant change in the baseline salinity of Upper Spencer Gulf has occurred in the past 25 years.

Salt loadings observed in the 1980s (on 12 occasions over a 30-month period) showed appreciable inter-annual variability: levels in mid-1983 and mid-1984 were significantly lower (by ~4 x 10^6 tonnes, equivalent to salinities ~1.0 g/L lower throughout Upper Spencer Gulf) than in mid-1982 (an El-Nino year). The salt loading on 6th August 2008 was almost identical to that seen on 28th July 1982.

In the absence of additional estimates of salt loading in recent times, the single value obtained in August 2008 may, as a worst case scenario, be interpreted as the minimum of an annual cycle that resembled that of 1983, rather than the much smaller cycle of 1982. If that were the case, it would imply that the mean salt loading of Upper Spencer Gulf may have increased by as much as ~4.5 x 10^6 tonnes, or ~1.1 g/L rise in salinity throughout the upper Gulf. If this were the case, it could have been caused by an observed increase in evaporation of ~3 x 10^{-3} mday^{-1} in the region. Such an effect implies a relationship between increased evaporation rates and increased upper Gulf salinity, quantified as ~1 g/L per 2.7 x 10^{-3} mday^{-1} increase in evaporation. Desalination of 200 GLyear^{-1} extracts the equivalent of ~2.2 x 10^{-5} mday^{-1} of freshwater from the total area (2.47 x 10^{10} m^2) of Spencer Gulf and may therefore, as a worst case estimate based on observed salinity variations, raise the salinity in Upper Spencer Gulf by up to 0.008 g/L.

Data Collection – 6th August 2008

Salinity was measured at 19 stations, shown in Figure 1 (the figure also shows depths to 1 decimal place, supplied by BMT WBM Pty Ltd at 2km-spaced grid point locations from their far-field numerical model).

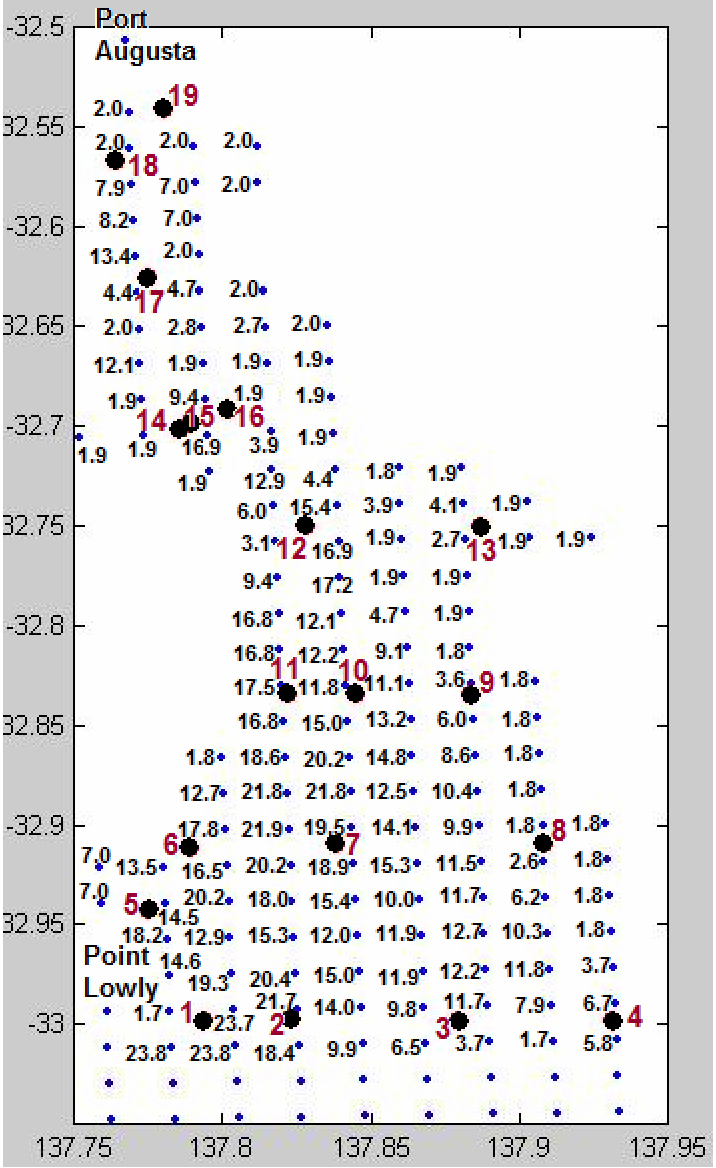

Figure 1: Depths and sampling stations

At most stations, salinity samples were collected from the surface (by bucket) and from a depth of approximately 1m above the sea bed (using a Nansen bottle triggered by releasing a metal ‘messenger’ along the suspension line). Stations with a total depth of less than 5m were only sampled at the surface (except for station 11). Two bottles were taken from each water sample in order to provide a cross-check for the subsequent measurement of salinity in the laboratory.

Table 1 shows station locations, sampling depths, bottle numbers and salinities (determined subsequently).

Laboratory-based, determination of salinity was carried out using the Flinders University Autolab salinometer on 15th August 2008. The electrical conductivity of a sample is compared with the electrical conductivity of a standard sample of seawater with precisely known salinity. The comparison yields a ‘conductivity ratio’ (CR, referenced to a salinity of 35.00 g/L[1]) from which the salinity is calculated using IAPSO[2] formulae. Standard seawater samples (of salinity 37.999 g/L) were obtained from OSIL[3] Ltd, UK, the only recognised provider of IAPSO Standard Seawater.

The procedure for measuring the salinity of seawater from upper Spencer Gulf differs from the process commonly performed because salinities are close to, or above the salinometer’s measurement limit of approximately 42 g/L. Precise dilution, using de-ionised water, is necessary to bring salinities down into measurable range.

All samples, including the IAPSO Standard Seawater samples, were placed in the measurement laboratory the afternoon before measurement (14th August), to allow them to equilibrate to the temperature of the laboratory.

At commencement of the process (the following morning), the salinometer was initialised as follows. Standard Samples indicate the conductivity ratio that the salinometer should read at various temperatures. At the temperature of the Flinders laboratory (15ºC) the CR of the 37.999 g/L water should be 1.07610.

Approximately 60ml of the sample was drawn up (under suction) to fill the measurement cell. The (five) CR dials were set to read 1.07610, the (two) temperature compensation dials were also set to represent the laboratory temperature, and the (four) ‘standardise’ dials were adjusted until the meter needle indicated a precise balance. Fluids that were previously in the measurement cell contaminate the new sample to a small extent causing incorrect measurement. For this reason, it is normal to repeat the adjustment twice more, discarding the measured fluid and re-filling the cell from the Standard sample bottle (total volume ~200ml) each time. Re-adjustment of the standardise dials should be relatively minor on the second filling, and almost no adjustment should be required on the third filling (as was the case). A standardise setting of ‘6396’ was required to balance the conductivity ratio of the Standard Seawater at its required CR of 1.07610. Once initialised, the standardise settings must not be changed unless re-calibrating against another Standard.

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[1] Oceanographic salinities are expressed in ‘practical salinity units’ (or psu), which are numerically equal to g/L. Despite oceanographic convention, salinities are expressed in g/L throughout this document.

[2] The International Association for the Physical Sciences of the Oceans http://iapso.sweweb.net/_db/index.php

[3] http://www.osil.co.uk/IAPSOSeawater/tabid/61/Default.aspx

Table 1 Station locations, bottle samples and salinities measured in Upper Spencer Gulf, 6th August 2008

Salinity Survey of Upper Spencer Gulf

Station	Latitude	Longitude	Time	Bottle	Depth	Salinity
1	32 59.88	137 47.63	0818	1	16m	41.24
				2		41.22
				3	Surface	41.25
				4		41.23
2	32 59.79	137 49.40	0830	5	23m	41.18
				6		41.17
				7	Surface	41.19
				8		41.20
3	32 59.85	137 52.74	0855	9	12m	41.42
				10		41.41
				11	Surface	41.36
				12		41.38
4	32 59.86	137 55.83	0910	13	7m	41.61
				14		41.59
5	32 56.59	137 46.47	1005	15	Surface	41.45
				16		41.44
				17	18m	41.43
				18		41.44
6	32 54.64	137 47.35	1025	19	Surface	41.40
				20		41.40
				21	18m	41.48
				22		41.49
7	32 54.53	137 50.31	1041	23	Surface	41.77
				24		41.77
				25	18m	41.81
				26		41.81
8	32 54.53	137 54.49	1108	27	Surface	42.13
				28		42.12
9	32 50.01	137 52.99	1120	29	Surface	42.04
				30		42.06
10	32 50.01	137 50.70	1150	31	Surface	42.02
				32		42.03
				33	12m	42.00
				34		42.00
11	32 50.01	137 49.32	1206	35	Surface	41.88
				36		41.87
				37	4m	41.85
				38		41.86
12	32 45.01	137 49.70	1235	39	Surface	error
				40		42.71
				41	12m	42.66
				42		42.66
13	32 45.00	137 53.19	1255	43	Surface	42.83
				44		42.83
14	32 42.13	137 47.13	1319	45	Surface	43.09
				46		43.11
15	32 41.88	137 47.32	1327	47	13m	43.11
				48		43.12
				49	Surface	42.97
				50		42.97
16	32 41.40	137 48.12	1345	51	Surface	43.18
				52		43.19
17	32 37.50	137 46.50	1400	53	Surface	43.32
				54		43.33
18	32 34.03	137 45.86	1425	55	Surface	44.15
				56		44.15
				57	6m	44.23
				58		44.24
19	32 32.48	137 46.80	1440	59	Surface	44.49
				60		44.49
				61	11m	44.55
				62		44.55

It is common practice to use a secondary standard when measuring many samples, because this allows the salinometer calibration to be re-checked without using another Standard Sample (as these are expensive). Immediately following initialisation, a sample from a significant (well-mixed) reservoir of seawater was measured (at 37.50 g/L) and further samples from the same source were used at approximately one hour intervals, to ensure that the salinometer's reading of CR for the secondary standard remained repeatable (within acceptable limits). Salinity of the secondary standard was repeatably measured at 37.50 g/L on all four occasions.

At the time of the Gulf survey, each water sample collected was decanted into two separate bottles (with consecutive bottle numbers). In the laboratory, one bottle of each pair was measured (to give its CR) until all station salinities were determined. Then the second bottle of each pair was measured, in reverse order, to provide a cross-check. All repeat measurements (except one, see below) gave a measured salinity within 0.02 g/L of the first sample.

The salinity of a Spencer Gulf sample was measured as follows. First, zero a digital balance under the weight of a clean, dry beaker to remove the beaker weight. Decant a single sample bottle of Gulf seawater into the beaker (taking care not to splash), and measure its weight (M_S, approximately 250g). Add a small quantity (approximately 30g) of de-ionised water to the beaker and measure the total weight (M_T). Mix the contents well. Measure the conductivity ratio of the diluted sample three times (in the usual way) until the measurement is steady. Convert the final CR to a salinity using standard formulae. Adjust the salinity by taking account of the dilution, ie, true salinity = measured salinity * M_T/M_S.

After measuring all samples from the Gulf, the secondary standard was re-measured for the last time (indicating that the salinometer had retained its calibration), and then a fresh IAPSO Standard was used to provide a primary re-calibration. This process generated a measured conductivity ratio of 1.07615 (which differed from the required value of 1.07610), although the discrepancy represented a calibration shift, during the five hours of measurement, of < 0.02 g/L from initialisation.

Table 1 shows the salinities measured from all bottles. In all cases (except one) the two bottle salinities agreed within 0.02 g/L. In one case (bottle 39), the third filling of the cell required a significant re-adjustment to achieve a balance, indicating probable contamination from another (unknown) source. In this case, the measured value was 42.65 g/L, but its companion sample was measured at 42.71 g/L. The measurement of bottle 39 is considered to be in error.

Salt Loading of Upper Spencer Gulf

The total salt content of upper Spencer Gulf was determined by assessing the salinity of each 2km x 2km cell and multiplying by the volume of the cell, summing over the entire upper gulf grid (see Figure 1).

It was necessary to estimate a mean depth at each grid point, taking account of the depth at surrounding points, in order to remove the bias associated with deep, narrow channels in the upper reaches of the Gulf. The model of Figure 2 shows the method, where the mean depth at point 'e', is calculated as[4]:

'e' = ['a' + 'c' + 'g' + 'i' + 2*'b' +2*'d' + 2*'f' + 2*'h' + 4*'e'] / 16

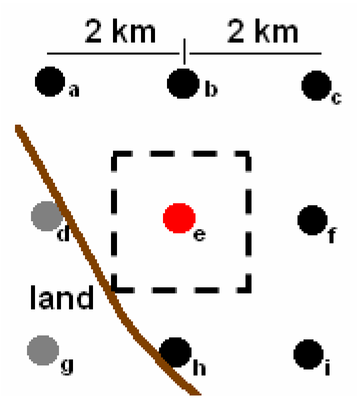

Figure 2 Cell pattern for mean depth calculation

Close to shore, and in the upper reaches, a number of the grid points in this calculation have zero depth. Figure 3 shows the mean depth (in metres) at the grid points of the WBM far-field model.

Figure 4 shows the depth-averaged salinity (mean of surface and deep salinities) at each of the stations sampled on 6th August 2008. From this figure, the salinity distribution was contoured, and a salinity was interpolated onto each grid point, as shown in Figure 5.

The total salt loading of Upper Spencer Gulf is then calculated as follows.

$$\text{Salt Loading} = a \sum_{i=1}^{n} s_i \bar{z}_i$$

where a is the area of a cell (2km x 2km), s_i is the salinity of the i^{th} cell, n is the number of cells (in this case 128) and $\bar{z}_i$ is the mean depth of the i^{th} cell. With salinity expressed in gl^{-3} (or kgm^{-3}) and other quantities expressed in metres, yields a salt loading in kilograms (easily converted to tonnes).

Figure 6 shows the cell-by-cell salt loading (in kilotonnes) calculated for the Upper Gulf as measured on 6th August 2008. The sum of salt in all cells, amounts to 1.818×10^8 tonnes.

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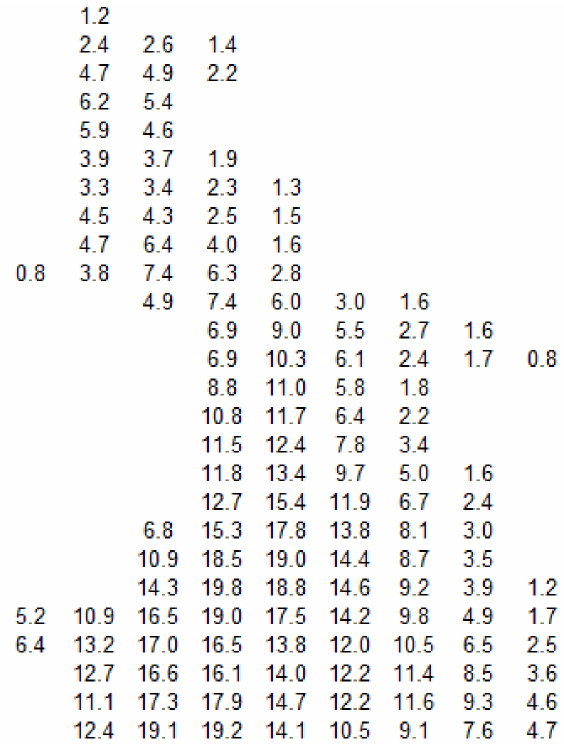
[4] Where 'a' is intended to imply the 'depth at grid point a', and similarly for all other points.



	1.2							
	2.4	2.6	1.4					
	4.7	4.9	2.2					
	6.2	5.4						
	5.9	4.6						
	3.9	3.7	1.9					
	3.3	3.4	2.3	1.3				
	4.5	4.3	2.5	1.5				
	4.7	6.4	4.0	1.6				
0.8	3.8	7.4	6.3	2.8				
		4.9	7.4	6.0	3.0	1.6		
			6.9	9.0	5.5	2.7	1.6	
			6.9	10.3	6.1	2.4	1.7	0.8
			8.8	11.0	5.8	1.8		
			10.8	11.7	6.4	2.2		
			11.5	12.4	7.8	3.4		
			11.8	13.4	9.7	5.0	1.6	
			12.7	15.4	11.9	6.7	2.4	
		6.8	15.3	17.8	13.8	8.1	3.0	
		10.9	18.5	19.0	14.4	8.7	3.5	
		14.3	19.8	18.8	14.6	9.2	3.9	1.2
5.2	10.9	16.5	19.0	17.5	14.2	9.8	4.9	1.7
6.4	13.2	17.0	16.5	13.8	12.0	10.5	6.5	2.5
	12.7	16.6	16.1	14.0	12.2	11.4	8.5	3.6
	11.1	17.3	17.9	14.7	12.2	11.6	9.3	4.6
	12.4	19.1	19.2	14.1	10.5	9.1	7.6	4.7

Figure 3. Mean depth (m) at each grid point

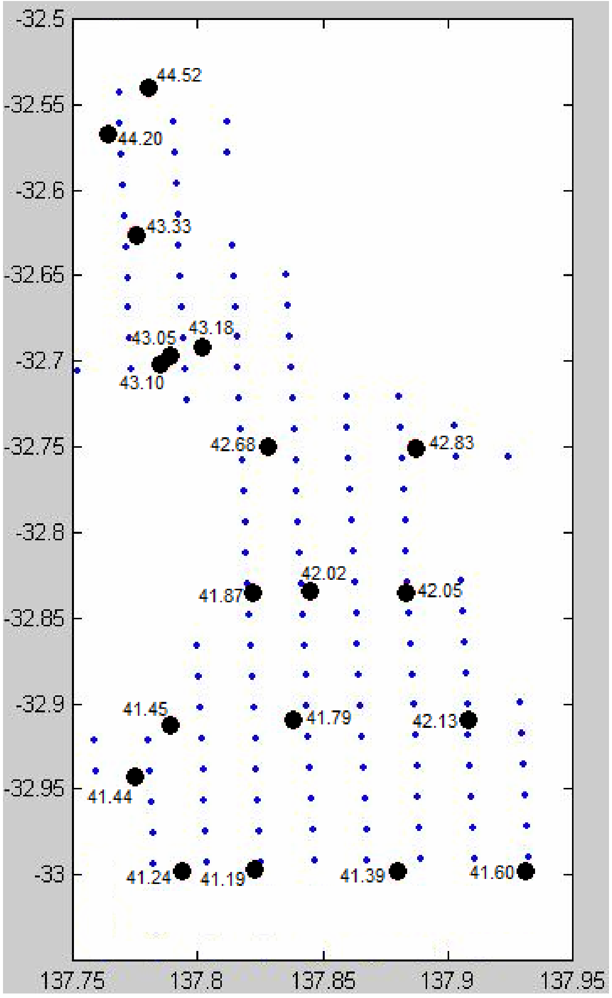
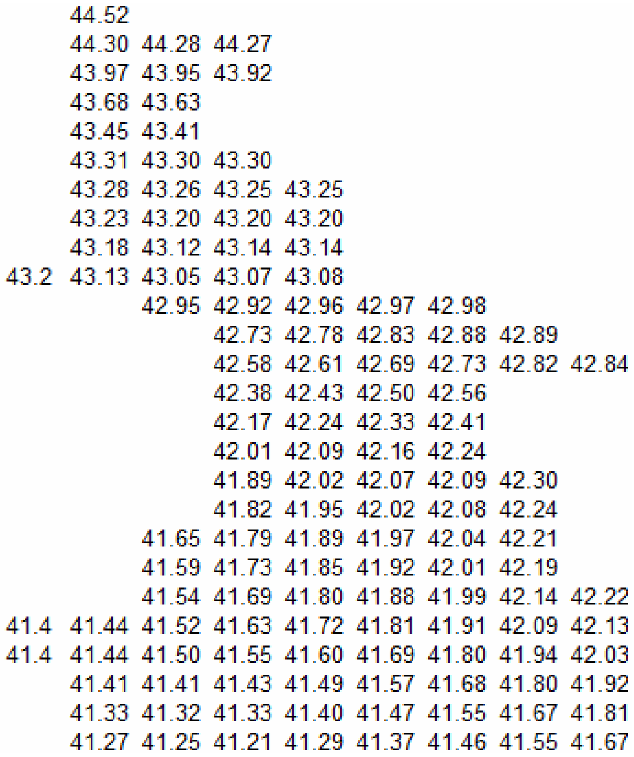
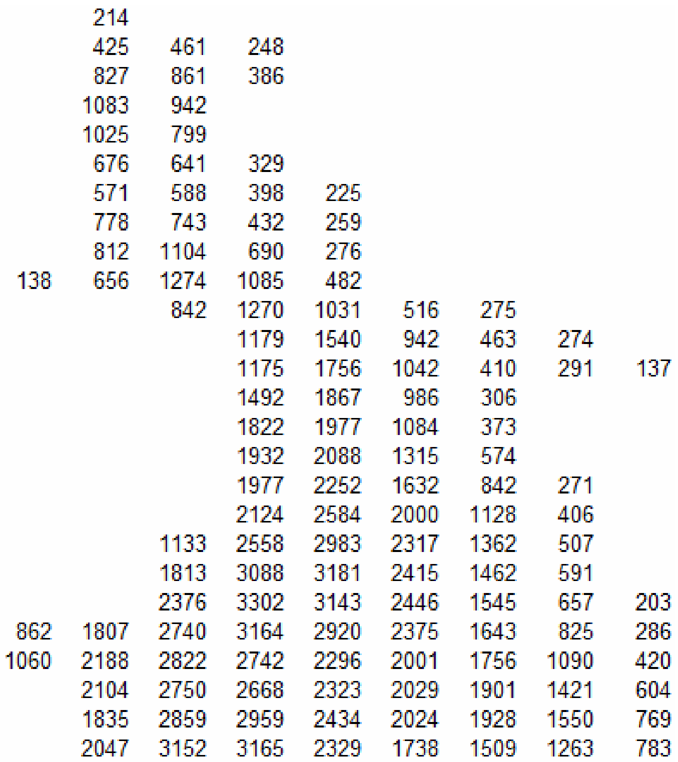


Figure 4 Mean salinity measured at each sampling station on 6th August 2008



	44.52							
	44.30	44.28	44.27					
	43.97	43.95	43.92					
	43.68	43.63						
	43.45	43.41						
	43.31	43.30	43.30					
	43.28	43.26	43.25	43.25				
	43.23	43.20	43.20	43.20				
	43.18	43.12	43.14	43.14				
43.2	43.13	43.05	43.07	43.08				
		42.95	42.92	42.96	42.97	42.98		
			42.73	42.78	42.83	42.88	42.89	
			42.58	42.61	42.69	42.73	42.82	42.84
			42.38	42.43	42.50	42.56		
			42.17	42.24	42.33	42.41		
			42.01	42.09	42.16	42.24		
			41.89	42.02	42.07	42.09	42.30	
			41.82	41.95	42.02	42.08	42.24	
		41.65	41.79	41.89	41.97	42.04	42.21	
		41.59	41.73	41.85	41.92	42.01	42.19	
		41.54	41.69	41.80	41.88	41.99	42.14	42.22
41.4	41.44	41.52	41.63	41.72	41.81	41.91	42.09	42.13
41.4	41.44	41.50	41.55	41.60	41.69	41.80	41.94	42.03
	41.41	41.41	41.43	41.49	41.57	41.68	41.80	41.92
	41.33	41.32	41.33	41.40	41.47	41.55	41.67	41.81
	41.27	41.25	41.21	41.29	41.37	41.46	41.55	41.67

Figure 5 Salinity interpolated onto all cells



	214							
	425	461	248					
	827	861	386					
	1083	942						
	1025	799						
	676	641	329					
	571	588	398	225				
	778	743	432	259				
	812	1104	690	276				
138	656	1274	1085	482				
		842	1270	1031	516	275		
			1179	1540	942	463	274	
			1175	1756	1042	410	291	137
			1492	1867	986	306		
			1822	1977	1084	373		
			1932	2088	1315	574		
			1977	2252	1632	842	271	
			2124	2584	2000	1128	406	
		1133	2558	2983	2317	1362	507	
		1813	3088	3181	2415	1462	591	
		2376	3302	3143	2446	1545	657	203
862	1807	2740	3164	2920	2375	1643	825	286
1060	2188	2822	2742	2296	2001	1756	1090	420
	2104	2750	2668	2323	2029	1901	1421	604
	1835	2859	2959	2434	2024	1928	1550	769
	2047	3152	3165	2329	1738	1509	1263	783

Figure 6 Cell-by-cell salt loading in kilotonnes

In the same way, the salt loading of Upper Spencer Gulf was calculated for each of the salinity distributions obtained during the 1980s, and compared with the current value (see Table 2).

Figure 7 shows the three annual (July to June) cycles of salt loading inferred from the twelve discrete surveys, with the latest (2008) survey included as a discrete point.

Table 2: Salt loadings in the 1980s and 2008

Date of Measurement	**Total Salt Loading (in Megatonnes)**
27 Jul 1982	**182.1**
24 Nov 1982	**180.5**
15 Jan 1983	**181.6**
9 Feb 1983	**182.9**
20 Apr 1983	**184.4**
22 Jun 1983	**180.6**
11 Aug 1983	**177.2**
1 Nov 1983	**177.6**
6 Mar 1984	**183.4**
26 Jun 1984	**182.2**
10 Oct 1984	**177.8**
23 Jan 1985	**180.1**
6 Aug 2008	**181.8**

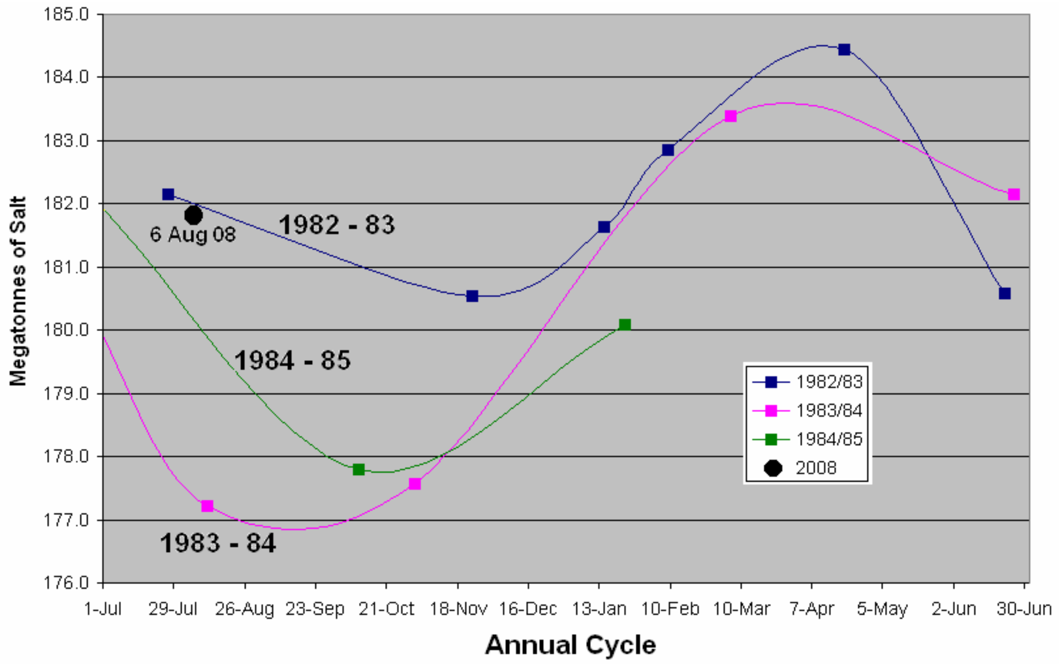


Figure 7 Measured Salt Loadings of Upper Spencer Gulf plotted as annual (July-to-June) cycles, to reveal relative means, amplitudes and phases.

Environmental Forcing

Figure 8[5] shows the trend of annual rainfall over Australia since 1970, indicating that the region around Spencer Gulf now receives ~37mm less rainfall per year, than it did in 1970. Figure 9 shows the trend of rising mean temperatures, and Figure 10 shows the trend of departure (anomaly) from the mean maximum temperature over the Murray-Darling basin, indicating daily maxima of a full 1.5ºC higher than 20 years ago. Figure 11 shows the anomaly across Australia, indicating that temperatures have consistently risen across almost the entire continent.

Figure 12 shows the comparison between daily maximum temperature and pan evaporation for the Murray-Darling basin, and Figure 13 provides the correlation of the two data sets, indicating that daily maximum temperature is a good proxy indicator of evaporation.

These data suggest that Spencer Gulf receives less rainfall (and runoff), and suffers greater evaporation than it did during the 1980s. Figure 14, provides three overlapping estimates of evaporation from Whyalla, Port Germein and Laura. This graphic is consistent with inferred trends, indicating rising evaporation rates since 2000, most notably in 2007.

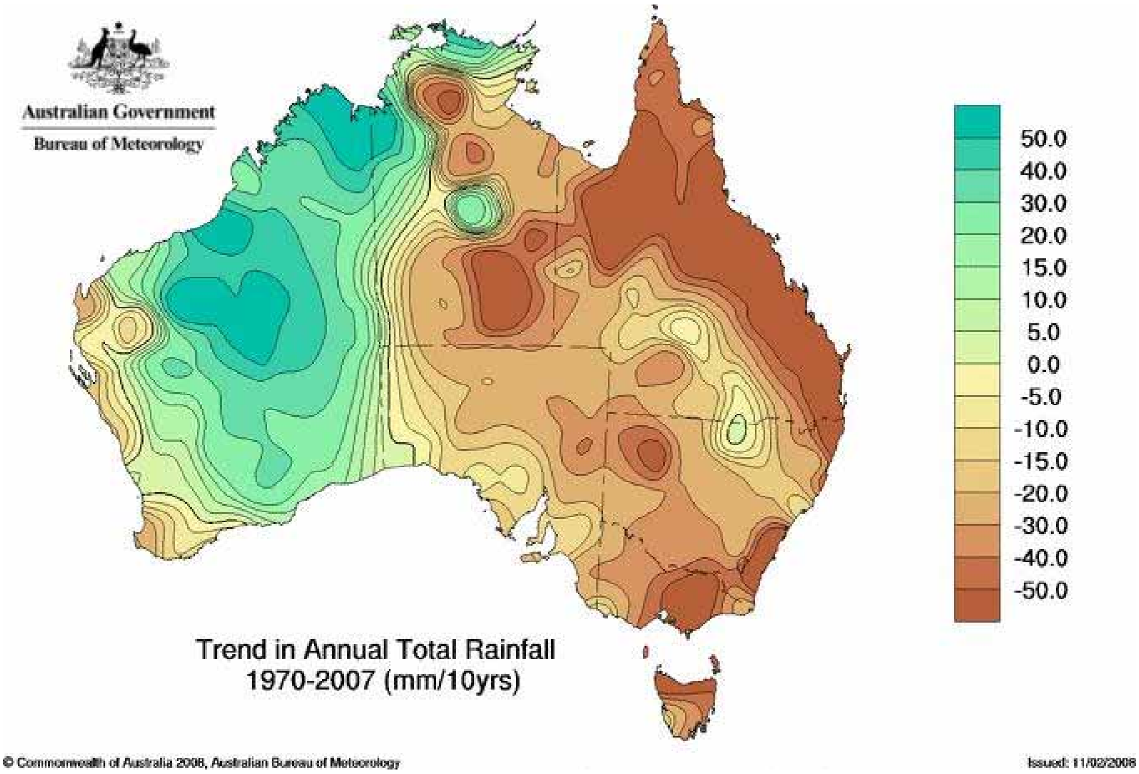


Figure 8: Annual rainfall in Australia since 1970

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[5] Figures 8 to 13 inclusive from http://tamino.wordpress.com/2008/05/30/drought-in-australia/

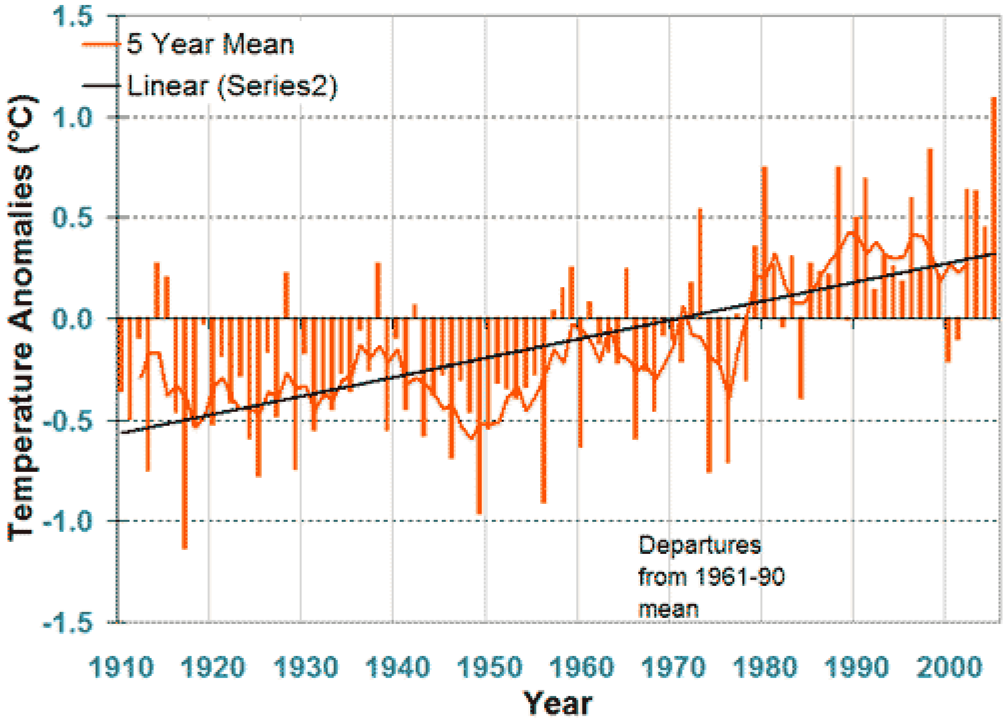

Figure 9. Ttrend of rising mean temperatures

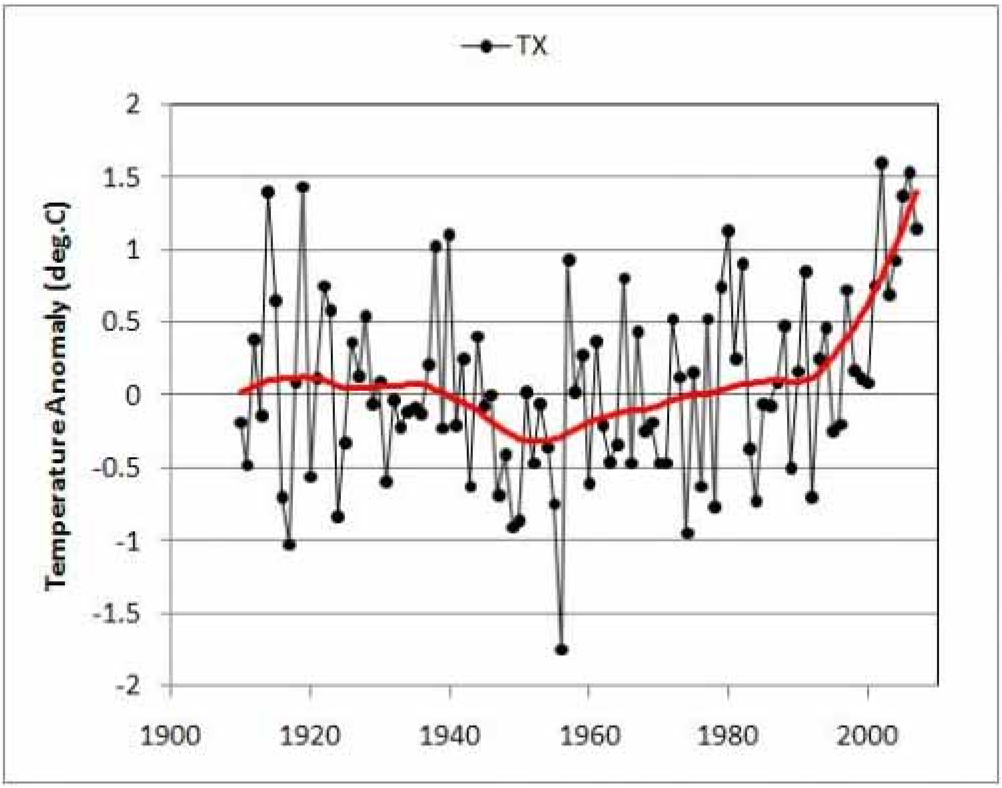

Figure 10. Trend of departure (anomaly) from the mean maximum temperature over the Murray-Darling basin

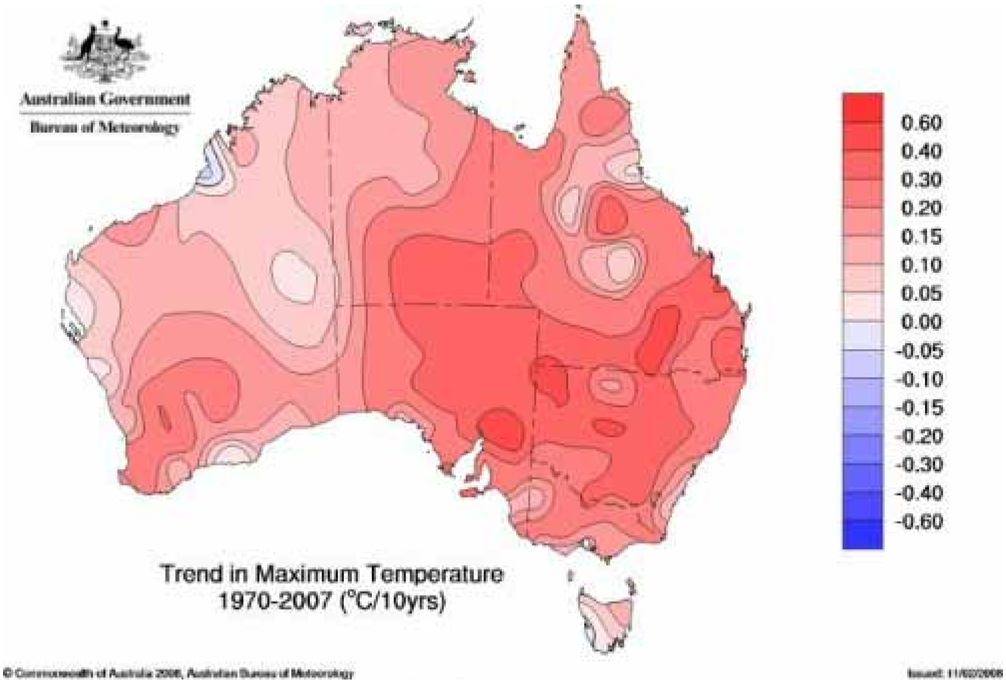

Figure 11. Trend of departure (anomaly) from the mean maximum temperature across Australia.

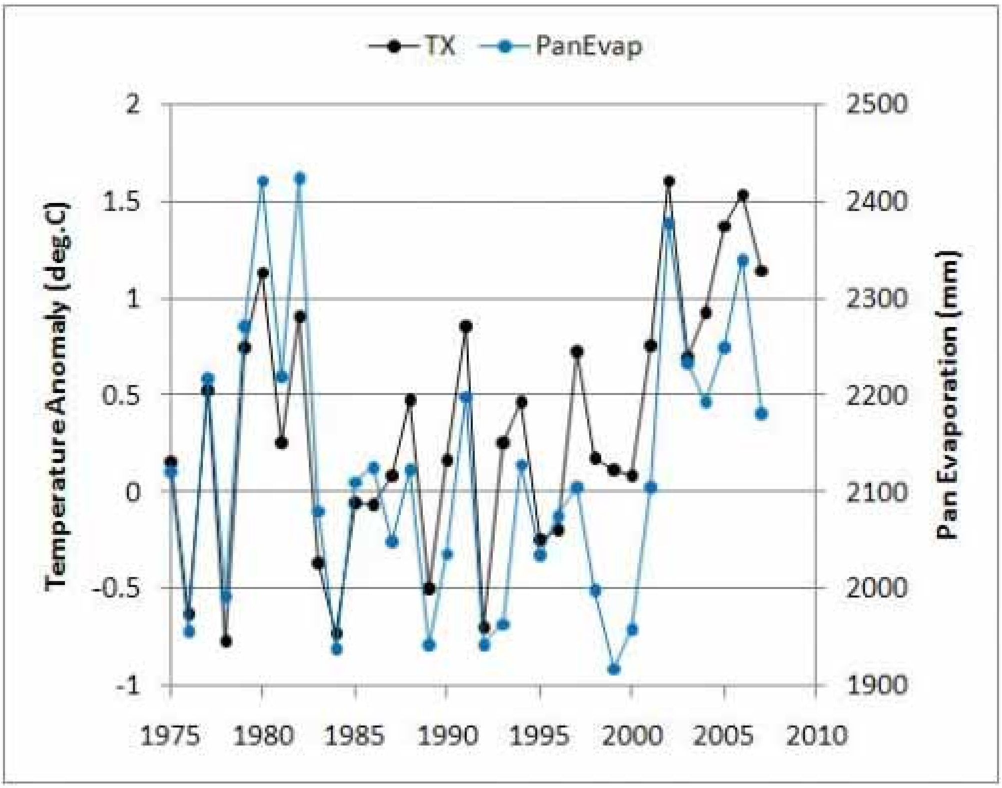

Figure 12. Comparison between daily maximum temperature and pan evaporation for the Murray-Darling basin.

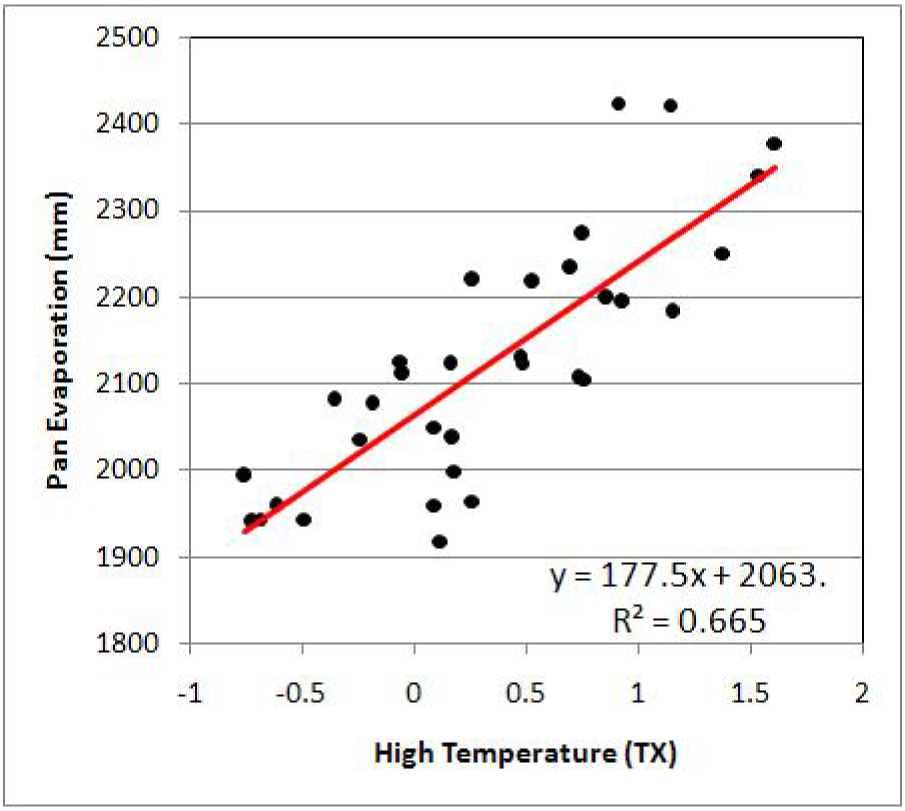

Figure 13. Correlation of between daily maximum temperature and pan evaporation for the Murray-Darling basin.

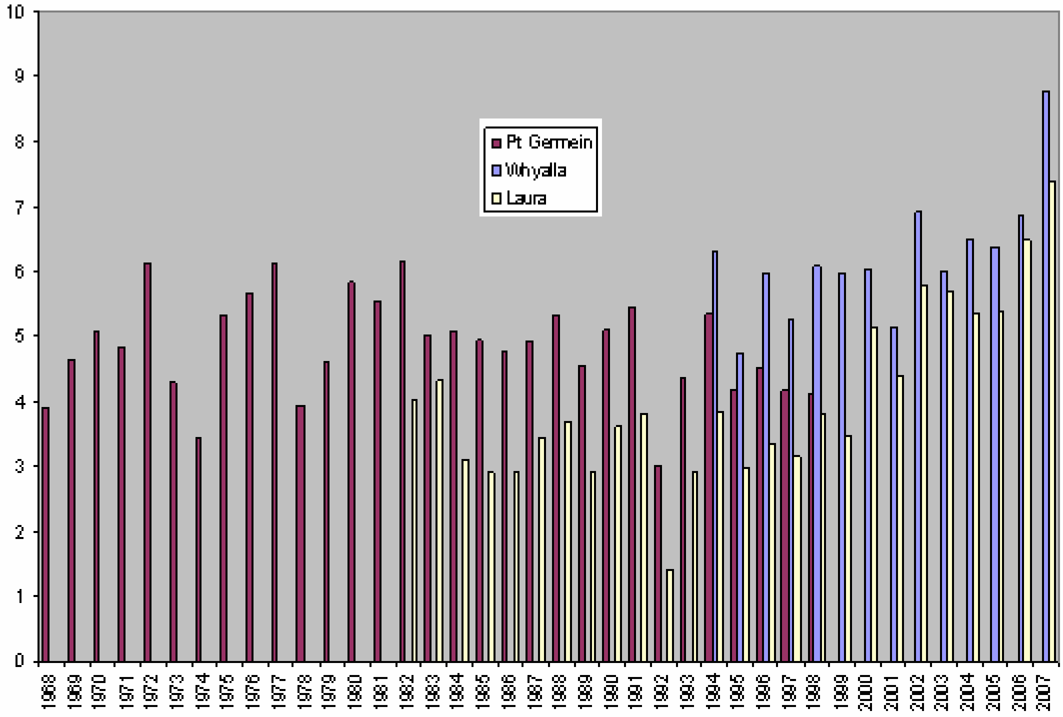

Figure 14 Measured Annual Evaporation (in mm day^{-1}) at three locations in the vicinity of Upper Spencer Gulf from 1968 to 2007

Interpretation of Salt Loadings

Observations through 30-months in the 1980s clearly show significant annual variability of salt loading. The Upper Gulf was relatively salty in mid 1982, and apparently failed to discharge much of the excess salt before further summer accumulation raised the loading to a peak of 184.5 Mt (in mid-April 1983). This was followed by a rapid and substantial discharge of salt to achieve the lowest measured salt loading (< 177.0 Mt) approximately 5 months later. Higher net evaporation caused accumulation again, through to early April 1984, achieving a peak of 183.5 Mt followed by a shallower decline through the latter part of 1984. The single measurement in 1985 suggested a relatively slower accumulation rate, although the annual evaporation in 1985 (Figure 8) was apparently similar to that of 1984, and Figure 8 lacks the intra-annual detail that would allow closer examination of this effect.

Figure 14 suggests that net evaporation in 1982 was some 20% higher than that in the three or four following years (based on measurements at Port Germein)[6]. Measurement of evaporation did not start at Whyalla until 1994 and has always been substantially higher than that at Port Germein. Using the implied relationship between evaporation at Port Germein and Whyalla would suggest that evaporation in Upper Spencer Gulf remained similar (with the possible exception of 2002 and 2006) to that measured in the 1980s, until 2007. Both Whyalla and Laura measurements suggest that 2007 was an anomalously hot/dry year.

Upper Spencer Gulf salinity reflects the combined effects of net evaporation (raising salinity due to freshwater removal) and mixing with the less saline waters further south, lowering salinity. To first order, the mixing effect might be considered constant throughout the year[7], and thus a long-term equilibrium salinity is established such that the accumulation of salt due to high net evaporation in the warmer months, is approximately balanced by the mixing effect in the cooler months. According to this model, the mean salinity of the Gulf should rise and fall with the inter-annual variation of net evaporation. On this basis, high net evaporation in 2007 would be expected to raise the mean salinity of Spencer Gulf. Observation of salinity in 2008 did indeed show relatively high salinity in August 2008 (compared with 1983 and 1984), although similar values were seen in 1982. It is interesting to note that Figure 12 (for the Murray-Darling Basin) indicates evaporation rates in 1982 that were similar to recent years, but were anomalously high compared to the intervening period.

It is difficult to interpret a single measurement of salt loading in 2008 to infer an annual mean. Two interpretations of the August 2008 salt loading are feasible and reasonable. Firstly, salinities may have been high during winter 2008 for the same reasons they were high in 1982, that is, due to higher than average net evaporation in preceding months. According to this ‘best case’ interpretation, the behaviour of Upper Spencer Gulf is much as it was some 25 years earlier, and there has not been any significant long-term change of mean salinity (salt loading) in Upper Spencer Gulf in the intervening period. In this interpretation, Spencer Gulf has no significant long-

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[6] A different interpretation might be made from measurements at Laura, which could be taken to imply that salinities in 1983/4 should have been higher than those in 1982/3 (which was not the case).

[7] This is not the case, but is adequately valid for this purpose.

term ‘memory’ of environmental forcing such as evaporation rates, and simply responds on a season-by-season basis.

The second interpretation, which might be seen as a ‘worst case’ scenario, assumes that the salt loading measured in August (2008) represents the minimum of an annual cycle that looks like that of 1983 rather than (the much smaller cycle of) 1982. If that were the case, it would imply that the mean salt loading of Upper Spencer Gulf may have increased by as much as ~4.5 x 10^6 tonnes, or ~1.1 g/L rise in salinity throughout the upper Gulf. If this were the case, it could have been caused by an observed increase in evaporation of ~3 x 10^{-3} $mday^{-1}$ in the region.

Such an effect implies a relationship between increased evaporation rates and increased upper Gulf salinity, quantified as ~1 g/L per 2.7 x 10^{-3} $mday^{-1}$ increase in evaporation. Desalination of 200 $GLyear^{-1}$ extracts the equivalent of ~2.2 x 10^{-5} $mday^{-1}$ of freshwater from the total area (2.47 x 10^{10} m^2) of Spencer Gulf and may therefore, as a worst case estimate based on observed salinity variations, raise the salinity in Upper Spencer Gulf by up to 0.008 g/L.