Long-term trends in the condition of seagrass meadows in Cockburn and Warnbro sounds

Margaret Mohring and Michael Rule

Technical Report to the Cockburn Sound Management Council

October 2013

Government of Western Australia
Department of Parks and Wildlife

Department of Parks and Wildlife

168 St Georges Terrace

Perth WA 6000

Tel: (08) 6467 5000

Fax: (08) 6467 5562

www.dec.wa.gov.au

ISSN [ISSN] (print)

ISSN [ISSN] (online)

ISBN [ISBN] (print)

ISBN [ISBN] (online)

This document is available in alternative formats on request.

Questions regarding the use of this material should be directed to:

Position

Department of Parks and Wildlife

Locked Bag 104

Bentley Delivery Centre

Western Australia 6983

The recommended reference for this publication is:
Mohring, M. and Rule, M. (2013) Long term trends in the condition of seagrass meadows in Cockburn and Warnbro sounds. Technical report to the Cockburn Sound Management Council.

Cover image reference/acknowledgment

Contents

Appendices

Figures

Tables

Acknowledgments

The authors wish to sincerely thank Dr. Andrea Whiting for her assistance with the trend analyses and GLMs, for providing the necessary R code, and for her patience in explaining these analyses. From DEC, we would also like to acknowledge Kathy Murray and Bart Huntley for GIS support and Corrine Severin who produced many of the plots in this report. Geoff Botting (CSMC) provided the historical water quality and seagrass data, and assisted with many requests. This report benefited from discussions with Dr. Tom Rose (CSMC) and Dr. Kim Friedman who also provided valuable comments on an earlier draft. Prof. Gary Kendrick provided a formal review and his comments and suggestions greatly improved the report..

Summary

Despite their ecological and economic importance, major declines in seagrasses extent and condition have been reported from Cockburn Sound in the Perth metropolitan area. Seagrass losses of approximately 80% between the 1960's and 1980s were attributed to a reduced light climate arising as a result of industrial inputs and resulting declines in water quality. Since 2004, the condition of seagrass meadows and adjacent water quality has been monitored across Cockburn Sound and adjacent Warnbro Sound, using a standardised sampling and reporting protocol. However, few attempts have been made to describe changes in seagrass condition in relation to these pressures. .

This project examined trends in the long term condition of seagrass meadows in Cockburn and Warnbro sounds. Further, we aimed to link trends in seagrass condition to identified pressures (natural, anthropogenic and climate change) acting on seagrass communities within the area.

We found a significant decline in seagrass density at almost all sites (including reference sites) across both Cockburn and Warnbro sounds. Several sites (Mangles Bay, Southern Flats, Kwinana, Luscombe Bay and Jervoise Bay) continue to experience significant anthropogenic pressure from different sources, although in general, most water quality parameters measured in both Cockburn and Warnbro sounds have improved over the past 10 years. Notable exceptions were, the concentration of chlorophyll *a* which has increased in recent years, and the level of dissolved oxygen, which has declined at many sites. The pressure of most concern to seagrass communities is summer sea temperature which has shown a significant increase in across all sites. This pressure is likely to continue to impact the seagrass community in future years.

The significant decline in seagrass contradicted the general improvement in water quality across both Cockburn and Warnbro sounds. The general decline in seagrass density across sites appears to most likely be a result of either: 1) a concomitant increase in water temperature across the area; 2) an artefact of the seagrass sampling regime (repeated disturbance associated with measuring seagrass in permanent quadrats) or 3), the study's inadequate characterisation of the pressure field, or a combination of these factors. In order to address each of these areas, and to better determine the key drivers of seagrass decline, specific recommendations are provided.

<u>Effect of increasing water temperatures</u>

We recommend that:

- a review of the literature around the effects of temperature on seagrasses coupled with experimental research is undertaken to better define the cause-effect pathway for increasing temperature;

- additional reference sites be established outside of Cockburn and Warnbro sounds which will, in time, provide a regional context for changes in the study area; and
- to provide a more immediate contextualisation, a review of historical seagrass data from existing research and monitoring programs around the region and a meta-analysis of trends is required.

<u>Repeated sampling impacting seagrass</u>

We recommend that:

- the CSMC implement an experimental study to determine the impact of repeated sampling of fixed quadrats on seagrass condition.

<u>Inadequate characterisation of pressures</u>

We recommend that:

- the CSMC investigate pathways to collect additional data to fill knowledge gaps of the pressures acting on seagrass in Cockburn Sound. Specifically, data concerning vessel use and anchoring is needed, as are data concerning the wave climate;
- for temperature and light, at least, *in situ* data loggers be deployed at several sites across the study area. This would provide a more suitable, continuous dataset against which changes in seagrass density could be assessed; and
- the cause-effect pathways between the recognised pressures and their potential indirect effects require further investigation (e.g. the link between PAR and sediment health will influence seagrass condition) through literature review and experimentation.

1 Introduction

Seagrass beds are widespread and productive ecosystems in both tropical to temperate regions (Hemminga and Duarte, 2000). Seagrass communities are keystone primary producers, and the combined productivity of seagrasses and associated flora ranks these communities among the most productive ecosystems on earth (Duarte, 2002; Heck et al., 2003). The coastline of Western Australia (WA) supports the largest and most diverse seagrass meadows in the world, with an estimated 2200 sq km of seagrass meadows, containing 26 species from 11 genera (Kirkman, 1997). These meadows sustain a high diversity of fauna (Heck et al., 2003), including commercially important species such as the western rock lobster, whiting, mullet, bream and snapper (Duarte and Cebrian, 1996; Heck et al., 2003). In WA, seagrasses are also of critical importance to some threatened fauna such as turtles and dugongs (Holley et al., 2006). Globally, seagrass beds are among the most valuable and threatened of marine habitats (Duarte, 2002; Short and Wyllie-Echeverria, 1996) that warrant careful conservation.

Despite the ecological and economic importance of seagrasses, major declines in extent and condition have been reported from several locations around the WA coast (e.g. Cockburn Sound, Oyster Harbour) particularly in response to the development of heavy industry and the discharge of industrial waste (Cambridge and McComb, 1984; Walker and McComb, 1990; Bastyan, 1986). The south-west coast of Western Australia is dominated by broken offshore islands, and submerged limestone reefs, which reduce the impact of ocean swells and allow for sand deposition. Around the Perth metropolitan area these geomorphic characteristics have created a large shallow coastal basin, Cockburn Sound, which supports significant seagrass communities (Carruthers et al., 2007). Cockburn Sound is situated close to industrial development and is under the most anthropogenic pressure of any marine embayment in WA. The boundaries of the area overseen by the Cockburn Sound Management Council (CSMC) extends across both the waters of Cockburn Sound and Owen Anchorage as well as their catchments, covering a marine area of about 170 sq km (Western Australian Auditor General, 2010). The area is important economically, socially and environmentally as it is used for multiple activities including commercial, industrial, aquaculture and recreational purposes. It is home to a vital part of the state's economy, incorporating the Kwinana industrial area, international shipping, port facilities, national defence, Perth's desalination plant and the largest snapper spawning area outside Shark Bay. The history of use and the diversity of activity in Cockburn Sound have placed considerable anthropogenic pressure on the marine environment over many decades. This coupled with a rapidly expanding human population and increasing use of the Sound, means that pressure on the marine environment continues to mount. The establishment of the CSMC in 2000 heralded a greater commitment to protecting the sound. Since this time improved industrial practices have resulted in a 95% reduction of direct disposal of environmentally damaging waste into the sound (Cockburn Sound Management Council, 2009).

Cockburn Sound historically supported large seagrass meadows which occupied approximately 4,000 ha, and covered most of the seabed at depths of 10 m or less. The extent of seagrass meadows in Cockburn Sound declined severely during the late 1960s and early 1970s and by 1978 it was estimated that only 872 ha (approximately 22%) of seagrass remained (Cambridge and McComb, 1984; Kendrick et al., 2002). The main cause of seagrass loss was identified as poor water quality arising primarily from industrial discharge (Cockburn Sound Management Council, 2009). As a consequence, there was a significant increase in the growth of filamentous algae and phytoplankton which reduced the light available to seagrasses (Cambridge et al., 1986). Additional, localised losses of seagrass were attributed to changes in turbidity, harbour construction and dredge spoil dumping, overgrazing by sea urchins and direct removal of seagrass by channel dredging, scallop dredging, boat moorings and anchor drag (Cambridge and McComb, 1984). In response to the decline, industry reduced its contaminant and nutrient discharges such that by the early 1980s water quality had improved (Western Australian Auditor General, 2010). Water quality declined again in the late 1980s, which triggered the Southern Metropolitan Coastal Waters Study (Department of Environmental Protection, 1996). This study determined that although seagrass dieback had slowed, nutrient-related water quality was only marginally better than it was in the late 1970s, and contaminated groundwater was now considered the main nitrogen input entering the sound. Controls on effluent input helped to arrest the decline but there was little evidence of regrowth (Cambridge et al., 1986; Kirkman, 1997), particularly on the eastern shelf of the sound (Kendrick et al., 2002). At the time mapping was last completed, only 661 ha of seagrass remained in Cockburn Sound (Kendrick et al., 2002), although this did not include Garden Island (T. Rose, pers. com). More recent mapping work conducted by UWA in 2013, suggest that the declines in the spatial extent of seagrass appear to have halted, with some areas showing re-growth in the order of hectares to 10s of hectares. This apparent re-growth has been concentrated around Mangles Bay and the northern end of Garden Island (G. Kendrick, pers. comms).

While seagrass meadows from Cockburn Sound have been monitored for many years (see Chapter 2), there have been few attempts at systematically assessing the long-term term trends in their condition. Lavery and McMahon (2011) examined trends in condition (i.e. shoot density) and found significant trends at several of the reference sites and one impact site. Since these observable trends at the reference sites are likely to affect the assessment of impact sites in Cockburn Sound, these authors recommended that trends in seagrass density be assessed annually at the Warnbro Sound reference sites.

Furthermore, few attempts have been made to describe seagrass condition in relation to the pressures acting on seagrass communities in Cockburn Sound. Here, we examined trends in both water quality and seagrass condition at all sites and compared them to reference conditions. In addition, we examined the relationship between water quality and seagrass condition in order to identify potential drivers of changes in seagrass condition. Finally, we have examined a number of components of the CSMC long term seagrass monitoring program and made recommendations to improve that program.

2 Trends in seagrass condition

2.1 Introduction

Seagrasses in Cockburn sound have been negatively impacted by anthropogenic pressure in and have shown significant declines in the past decades (Kendrick et al., 2002). In 1994, the then Department of Environment and Conservation (DEC) commissioned Edith Cowan University (ECU) to assess seagrass health at locations throughout Cockburn Sound and adjacent Warnbro Sound. The initial health assessment (Lavery, 1994) was complemented by a simultaneous assessment of changes in seagrass area in the region (Kendrick et al., 2002). Since 1998 the survey of seagrass health has been repeated annually, in January, on behalf of the DEC and the Cockburn Sound Management Council (CSMC). Since 2000, the CSMC has commissioned seagrass monitoring where surveys incorporated quantitative measurements of a number of variables at assessment sites throughout Cockburn Sound and reference sites in Warnbro Sound. In 2004, the program was reviewed (Environmental Protection Authority, 2005) and a standardised methodology for data collection, reporting and assessment was implemented (Environmental Protection Authority, 2004).

While patterns in seagrass condition in Cockburn Sound have been examined by some authors (Lavery and Gartner, 2008; Lavery and McMahon, 2011, 2007), long term trends in condition have not been examined in detail across all sites. Lavery and McMahon (2011) examined trends the Warnbro Sound sites in order to determine their continued suitability as reference areas. These authors found declining trends in a number of the reference sites, but concluded that these trends did not invalidate their use as reference areas. Other than the annual assessment against the Environmental Quality Standards (Environmental Protection Authority, 2005), the density of seagrass at impact sites has rarely been compared to the reference sites. Furthermore, seagrass density has not been linked to the pressures that are recognised at each site (See Chapter 4).

Here we examined long-term trends in seagrass density in Cockburn and Warnbro sounds using data collected under the CSMC seagrass monitoring program since data collection began under the standardised protocol (Environmental Protection Authority, 2004). In addition, we compared densities at each site to densities at corresponding reference sites, which were defined using a GIS approach.

2.2 Methods

2.2.1 Collection of Seagrass trend data

Seagrass community condition was surveyed annually at 12 ‘health’ sites, four ‘test reference’ sites, five ‘reference’ sites and four ‘depth transect’ sites (Figure 1). A description of the each of these sites is provided in Lavery and Gartner (2008). ‘Health’

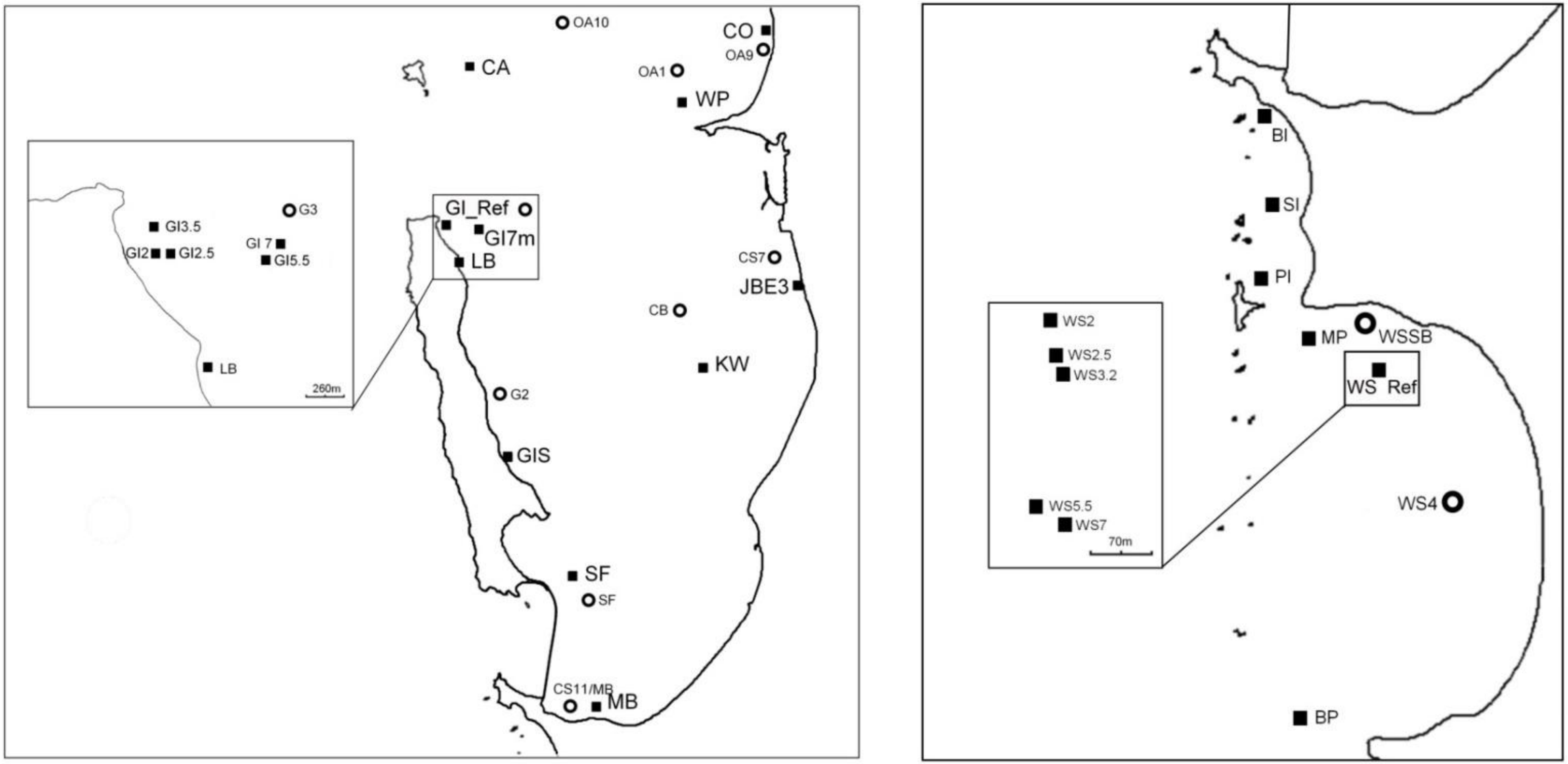


Figure 1 - Maps displaying the seagrass (solid square) and water quality (hollow circle) monitoring sites in Cockburn Sound (left) and Warnbro Sound (right).

sites are ones which may be impacted by activity in Cockburn Sound; ‘test reference’ sites were originally established as additional reference sites, but due to concerns over their proximity to the impact sites, and lack of spatial independence, were rejected from the monitoring program (Lavery and McMahon, 2011). Despite not being part of the formal CSMC seagrass program, data has continued to be collected from these sites. Here, we have combined ‘health’ and ‘test reference’ sites and named them ‘impact’ sites. Additionally, the ‘depth transect’ sites have not been assessed here, as trends in seagrass condition would likely be confounded by the addition of depth as a factor.

At each site, shoots of *Posidonia sinuosa* and *Posidonia australis* were counted by SCUBA divers in 24 permanently marked 20 x 20 cm quadrats at according to the Standard Operating Procedures (Environmental Protection Authority, 2004).

2.2.2 Analysis and presentation of seagrass data

We performed two analyses on seagrass shoot density data. Firstly, we investigated long-term trends in mean seagrass density at each site by fitting a Generalised Additive Model (GAM) (Wood and Augustin, 2002) using the *mgcv* package in R (R Core Team, 2013; Wood, 2010). We examined trends at both a significance level of $\alpha = 0.05$ and $\alpha = 0.2$, as we were interested in general declines in seagrass density. Power analyses on trend data were conducted using the program TRENDS (Gerrodette, 1993a, 1993b), with a one-tailed significance test to highlight declines in the seagrass population. Where a significant trend did not achieve a power of 0.8, we calculated the minimum number of years’ data required to achieve this level of confidence in the results. For the input into the TRENDS program, the coefficient of variation was calculated using de-trended data (i.e. residuals) so the dispersion of observations was not overestimated.

Next, we used a two factor Repeated Measures Analysis of Variance (RM ANOVA) to compare mean seagrass densities between impact and reference sites, and to determine if seagrass densities had changed over time. Prior to analysis, all data were checked for homogeneity of variance using Cochran’s Test and were appropriately transformed where necessary. In addition, a Mauchly’s Test was used to examine sphericity, and where significant, the degrees of freedom for the test were adjusted by multiplying the degrees of freedom by the Greenhouse-Geisser epsilon estimate. Where significant Site x Time interactions were returned, pairwise tests (t tests) between sites within each year were performed. RM ANOVAs were performed in SPSS.

2.2.3 Seagrass site bathymetry

Under the Environmental Quality Standards (EQS, Environmental Protection Authority, 2005) for the Cockburn Sound seagrass monitoring program, median seagrass shoot density from an ‘impact’ site is compared to either the 95^{th} or 80^{th} percentile values from the appropriate reference site (i.e. site at approximately same depth). Reference and impact sites were established over a relatively narrow depth range (i.e. 2, 2.5, 3.2, 5.5 and 7m) primarily to monitor changes in the light environment in Cockburn Sound. The depth of these sites was initially measured *in situ* by Lavery and Gartner (2008), and again by the Centre for Marine Futures (2009) who reported discrepancies in the depths of some sites. The latter recommended that the depths of all sites be checked so impact sites would be compared to the appropriate reference sites, as comparing seagrass densities to the incorrect reference site could lead to a misinterpretation of the EQS. Further, Lavery and McMahon (2011) recommended formalising criteria in the Standard Operating Procedure (SOP; Environmental Protection Authority, 2004) to assist selecting appropriate reference sites against which to assess seagrass density in Cockburn Sound.

Prior to comparing impact and reference sites, we performed an analysis to determine the correct reference depths for each impact site. We examined a high-resolution (5 x 5 m pixel) bathymetry GIS layer (Appendix 2) that had been corrected for tidal deviations (Fugro LADS Corp, 2009). These data were captured using a LADS MK II Airborne LiDAR Bathymetry System. From this layer we calculated the depth of each site. Depth was taken from the central picket at each site, as sites are relatively homogeneous in depth (Lavery and Gartner, 2008). For this report, where discrepancies have been found, we have assessed seagrass condition against both the historical reference site and the most appropriate reference site as determined from the bathymetry data.

2.3 Results

2.3.1 Trends in seagrass

Of the 16 impact sites, 10 revealed significant negative trends in seagrass density at p = 0.2; Garden Island Settlement, Kwinana, Luscombe Bay, Southern Flats, Jervoise Bay, Bird Island, Garden Island 2.0, 3.2, 5.5 and 7.0m (Table 1; Figure 2; Figure 3). All of the reference sites returned significant negative trends in density at p = 0.2 (Table 1; Figure 3). Only Luscombe Bay and Warnbro Sound 2.5m did not achieve a power of 0.8 and would require five and six further years of sampling, respectively, to achieve significant trends at this level of power (Table 1).

When the significance level was reduced to a more conservative $\alpha = 0.05$, significant declines in seagrass density were only observed at Garden Island Settlement, Southern Flats and Jervoise Bay, Garden Island 3.2 and 5.5 and at the Warnbro Sound 2.0, 3.2 and 5.5m sites (Table 1). The power of these trends only reached 0.8 at Garden Island Settlement, Garden Island 3.2m and 5.5m, and at Warnbro Sound 3.2m and 5.5m. The remaining sites require between 2 and 24 additional years' data to reach the desired power level (Table 1).

Table 1 – Summary of the trend and power analyses for seagrass density. The F-statistic, P-value, Coefficient of Variation and the Trend are shown for each site. Also shown are the power of each trend and the estimated minimum number of years before a significant trend can be calculated. Trends significant at p = 0.2 are shown in bold. '+' = trends reached the desired power level of 0.8; '-' = minimum number of years to reach a power of 0.8 could not be calculated.

		Trend Analysis				Power Analysis			
Site	Years of data	*P*	*F*	CV	Trend	Power (α = 0.2)	Min. years (α = 0.2)	Power (α = 0.05)	Min. years (α = 0.05)
Carnac Island	8	0.34	1.07	0.13	-0.14	0.57	25	0.24	-
Coogee	7	0.21	0.16	0.18	-0.08	0.33	-	0.10	-
Garden Is. Settlement	**7**	**0.01**	**14.80**	**0.12**	**-0.46**	**>0.99**	**+**	**0.94**	**+**
Kwinana	**9**	**0.08**	**4.09**	**0.15**	**-0.29**	**0.87**	**+**	**0.57**	**17**
Luscombe Bay	**8**	**0.18**	**2.40**	**0.13**	**-0.19**	**0.67**	**13**	**0.31**	**32**
Mangles Bay	9	0.84	0.04	0.26	-0.06	0.27	-	0.08	-
Southern Flats	**11**	**0.03**	**6.22**	**0.13**	**-0.28**	**0.94**	**+**	**0.72**	**13**
Woodman Point	8	0.46	0.61	0.19	-0.73	>0.99	+	>0.99	+
Jervoise Bay	**9**	**0.03**	**7.57**	**0.26**	**-0.56**	**0.94**	**+**	**0.73**	**12**
Bird Island	**8**	**0.17**	**2.43**	**0.14**	**-0.26**	**0.84**	**+**	**0.52**	**17**
Mersey Point	8	0.53	0.45	0.21	-0.20	0.52	-	0.21	-
Garden Island 2.0m	**9**	**0.09**	**3.83**	**0.08**	**-0.17**	**0.88**	**+**	**0.58**	**17**
Garden Island 2.5m	11	0.53	0.43	0.23	-0.14	0.43	-	0.15	-
Garden Island 3.2m	**11**	**<0.01**	**20.42**	**0.13**	**-0.46**	**>0.99**	**+**	**0.98**	**+**
Garden Island 5.5m	**11**	**<0.001**	**36.93**	**0.10**	**-0.47**	**>0.99**	**+**	**>0.99**	**+**
Garden Island 7.0m	**11**	**0.06**	**4.46**	**0.25**	**-0.42**	**0.86**	**+**	**0.57**	**22**
Warnbro Sound 2.0m	**11**	**<0.001**	**36.09**	**0.11**	**-0.48**	**>0.99**	**+**	**>0.99**	**+**
Warnbro Sound 2.5m	**11**	**0.17**	**2.19**	**0.17**	**-0.22**	**0.72**	**17**	**0.38**	**-**
Warnbro Sound 3.2m	**11**	**0.01**	**13.89**	**0.24**	**-0.61**	**>0.99**	**+**	**0.91**	**+**
Warnbro Sound 5.5m	**11**	**<0.01**	**20.16**	**0.12**	**-0.44**	**>0.99**	**+**	**0.99**	**+**
Warnbro Sound 7.0m	**9**	**0.10**	**3.58**	**0.14**	**-0.25**	**0.84**	**+**	**0.53**	**19**

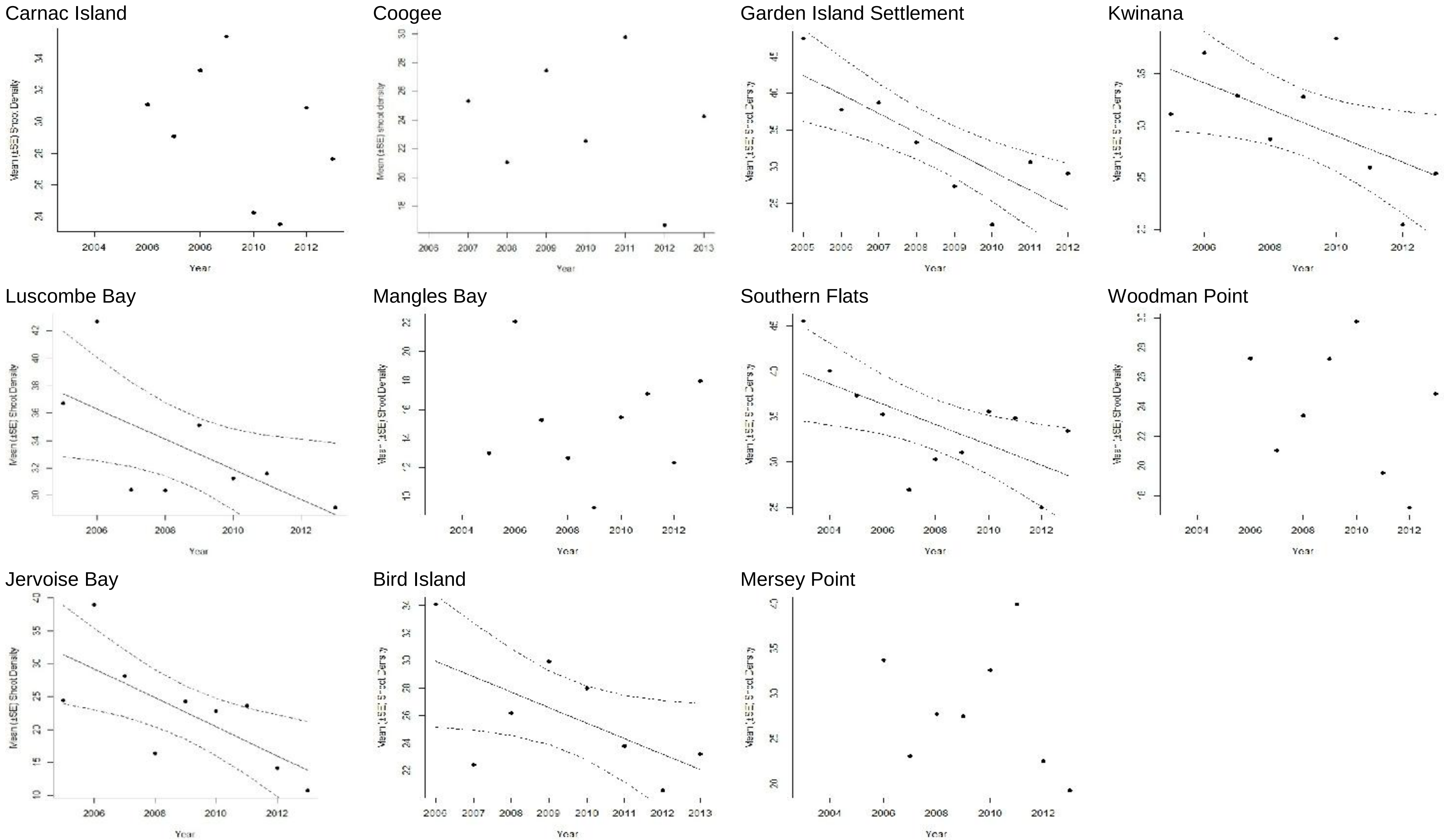


Figure 2 – Mean seagrass densities at all impact sites from 2003-2013. Where significant (p = 0.2) trends existed the trend line (solid line) and the 95% confidence intervals (dotted line) are displayed.

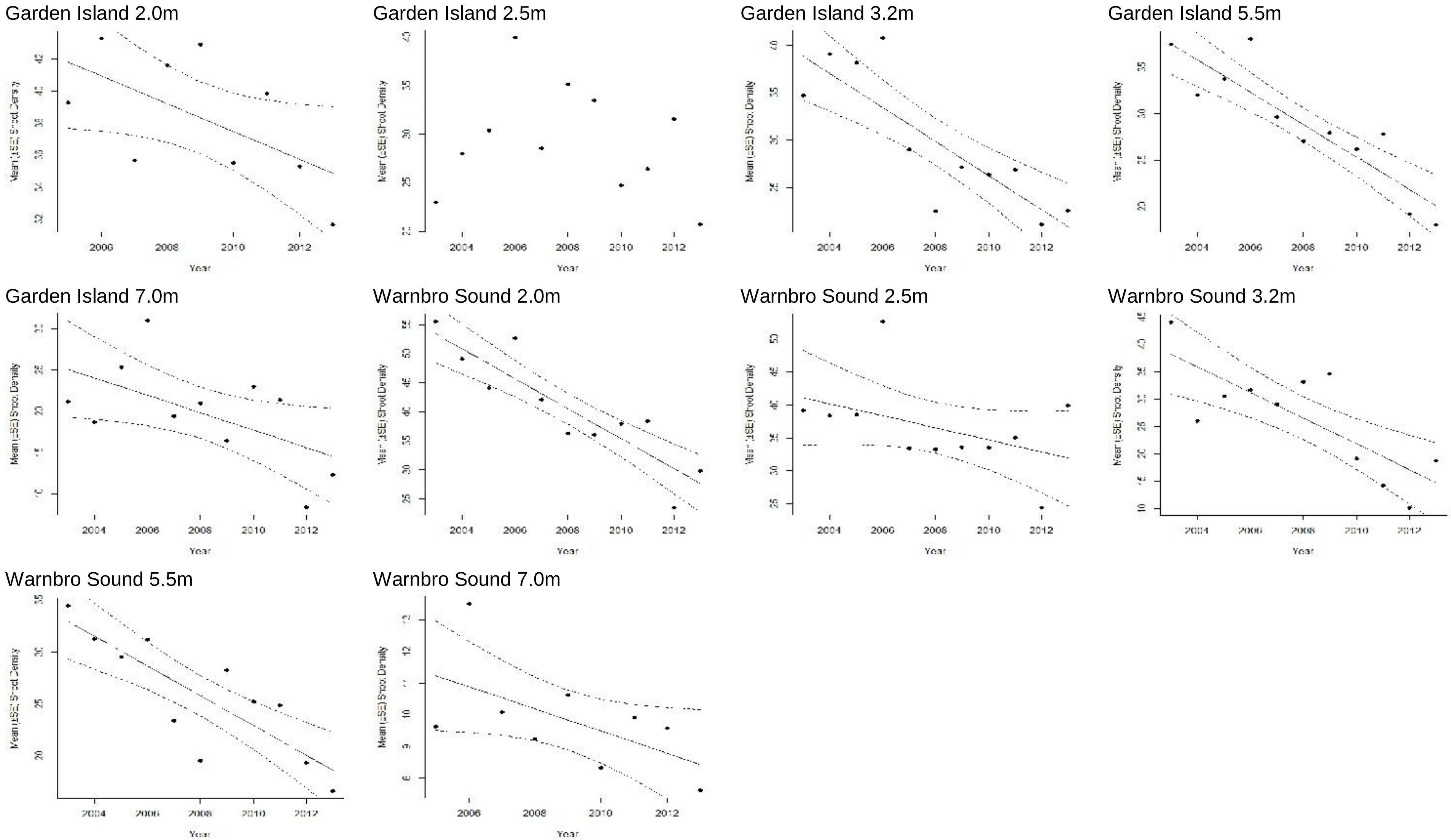


Figure 3 - Mean seagrass densities at the Garden Island impact sites and all reference sites from 2003-2013. Where significant (p = 0.2) trends existed the trend line (solid line) and the 95% confidence intervals (dotted line) are displayed.

2.3.2 Seagrass density at impact versus reference sites

With the exception of Woodman Point, there was significant within-site variability in the density of seagrass over time (Table 2). There was a significant Site effect (i.e. no significant interaction term) for the comparisons between Garden Island Settlement, Luscombe Bay, Woodman Point, Garden Island 5.5m and Kwinana and their respective reference sites (Table 2). With the exception of Kwinana and Garden Island 5.5m, all of these sites had significantly lower seagrass densities than the reference sites.

A significant Site x Time interaction was returned for the majority of comparisons, suggesting that the effect of Time was not consistent across Sites (Table 2). Of the sites that were only compared to their original reference depths, Garden Island 2.0m, Mangles Bay and Garden Island 3.2m returned significant interactions. Densities at Garden Island 3.2m and Garden Island 2.0m were significantly different from the corresponding reference sites during one and two of the 11 years, respectively. The densities at Mangles Bay were significantly lower than Warnbro Sound 3.2m in six of the years from 2003-2013.

The sites that were compared to both their original reference depth, and new calculated reference depth generally returned significant interactions for both comparisons. For Bird Island, the comparisons with both reference sites (Warnbro Sound 2.0m and 2.5m) returned significant lower densities at Bird Island in 2006, 2007, 2011 and 2013. The comparison between Southern Flats and Warnbro Sound 2.0m returned significantly lower denisities at Southern Flats in 2006 and 2007; however, when compared to Warnbro Sound 2.5m, only the comparison within 2006 was significant. When Mersey Point was compared to Warnbro Sound 2.5m, there were differences in seagrass density during 2006, 2007 and 2013, with density lower at Mersey Point; but when compared to Warnbro Sound 3.2m, a difference was revealed in 2011 and 2013.

While there was a significant interaction for the Garden Island 7.0m vs Warnbro Sound 7.0m comparison, there was no interaction, and indeed, no site effect, for the Garden Island 7.0 vs Warnbro Sound 5.5m comparison. This is further evidence that this site has been historically compared to an inappropriate reference site and needs to be revised.

2.3.3 Bathymetry (depth)

While most sites were very similar to the original measured depths, several (Southern Flats, Bird Island, Mersey Point and Garden Island 7.0m) were found to be different to those that were assigned when the program commenced (Table 3). Of greatest concern is the Garden Island 7.0m site which is closer to 5.5m, and should be compared to the Warnbro Sound 5.5m site rather than the Warnbro Sound 7.0m site that it has historically been compared to. Additionally, the Warnbro Sound 3.2m site is actually closer to 2.5m, meaning there is no true reference site at 3.2m.

These results have implications for the interpretation of seagrass health at these sites, and we recommend that the reference sites against which these are compared be revised for the longer term monitoring program. This may also require a retrospective analysis of seagrass condition at these sites.

*Table 2 – Summary of the RM ANOVA comparing seagrass density between impact and reference sites. Where significant Site x Year interactions were returned, pairwise comparisons between sites between within each year are presented. * = p < 0.05, ** = p < 0.01, *** = p < 0.001.*

		Site		Year		Site*Year		Pairwise comparison between sites in each year										
Impact site	Ref. site depth	F	P	F	P	F	P	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Carnac Island	3.2m	1.030	0.319	4.718	**0.001**	1.924	0.104											
Coogee	5.5m	0.668	0.418	6.117	**<0.001**	1.626	0.140											
Garden Is. 7.0m	5.5m	1.005	0.323	7.512	**<0.001**	1.631	0.132											
	7.0m	38.958	**<0.001**	10.411	**<0.001**	3.925	**0.002**			***	***	***	***	*	***	**		
Garden Is. Settle.	2.0m	6.782	**0.013**	7.226	**<0.001**	2.213	0.066											
Kwinana	5.5m	8.807	**0.005**	9.824	**<0.001**	1.896	0.081											
Luscombe Bay	2.0m	7.637	**0.009**	7.404	**0.000**	1.481	0.198											
Mangles Bay	3.2m	33.176	**<0.001**	5.768	**<0.001**	4.381	**0.001**			*	**	***	***	***				***
Southern Flats	2.0m	14.663	**<0.001**	10.730	**<0.001**	3.150	**0.005**				***	***						
	2.5m	3.859	0.056	10.982	**<0.001**	3.014	**0.005**				***							
Woodman Point	3.2m	8.203	**0.024**	1.967	0.079	0.959	0.471											
Jervoise Bay	3.2m	0.009	0.925	4.372	**0.007**	2.688	0.054											
Bird Island	2.0m	21.339	**<0.001**	5.112	**0.001**	3.166	**0.014**				***	***				*		*
	2.5m	16.630	**<0.001**	8.221	**<0.001**	2.509	**0.032**				**	*				**		***
Mersey Point	2.5m	7.437	**0.009**	10.563	**<0.001**	3.855	**0.003**				**	*						***
	3.2m	0.431	0.925	2.732	**0.010**	3.049	**0.005**									*		***
Garden Is. 2.0m	2.0m	1.376	0.248	6.249	**<0.001**	5.541	**<0.001**	*		***								-
Garden Is. 2.5m	2.5m	4.022	0.053	6.417	**<0.001**	6.168	**<0.001**	***	*		*							***
Garden Is. 3.2m	3.2m	0.048	0.828	2.893	**0.020**	2.759	**0.025**											*
Garden Is. 5.5m	5.5m	4.573	**0.038**	13.985	**<0.001**	0.868	0.530											

Table 3 – List of permanent seagrass sites, their impact designation (impact/reference), the original measured depths (from Lavery and Gartner, 2008) and their reference counterparts. Also shown are the depths calculated from the high resolution LiDAR bathymetry layer (Fugro LADS Corp, 2009) and the correct reference depths against which each impact site should be compared. Sites where the calculated comparison depth is different to the original reference comparison are shown in bold.

			Original *in situ* measured depth		Depth calculated from bathymetry	
Site name	Site type	Years sampled	Site depth	Assessed against	Impact site	Ref. comparison
Carnac Island	Impact	2005-2013	4.5	3.2	3.59	3.2
Coogee	Impact	2007-2013	5.0	5.5	5.76	5.5
Garden Is. Settlement	Impact	2002-2008, 2013	2.0	2.0	1.14	2.0
Kwinana	Impact	1998-2013	5.2	5.5	4.68	5.5
Luscombe Bay	Impact	2002-2008, 2013	2.0	2.0	1.27	2.0
Mangles Bay	Impact	1998-2013	3.2	3.2	3.32	3.2
Southern Flats	**Impact**	**1998-2013**	**2.5**	**2.5**	**2.14**	**2.0**
Woodman Point	Impact	2008-2013	2.5	3.2	3.75	3.2
Jervoise Bay	Impact	2002-2013	2.5	3.2	3.51	3.2
Bird Island	**Impact**	**1998-2013**	**2.0**	**2.5**	**1.85**	**2.0**
Mersey Point	**Impact**	**1998-2013**	**3.0**	**3.2**	**2.33**	**2.5**
Garden Island 2.0m	Impact	2003, 2005-2013	2.0	2.0	1.91	2.0
Garden Island 2.5m	Impact	2003-2013	2.5	2.5	2.62	2.5
Garden Island 3.2m	Impact	2003-2013	3.2	3.2	3.11	3.2
Garden Island 5.5m	Impact	2003-2013	5.5	5.5	4.78	5.5
Garden Island 7.0	**Impact**	**1998-2013**	**7.0**	**7.0**	**5.79**	**5.5**
Warnbro Sound 2.0m	Reference	2003-2013	2.0	-	2.09	-
Warnbro sound 2.5m	Reference	2003-2013	2.5	-	2.38	-
Warnbro Sound 3.2m	**Reference**	**2003-2013**	**3.2**	**-**	**2.76**	**-**
Warnbro Sound 5.5m	Reference	2003-2013	5.5	-	5.0	-
Warnbro Sound 7.0m	Reference	2005-2013	7.0	-	7.0	-

2.4 General Discussion

This study has found a number of issues with the both the long term monitoring program and how sites are compared under the EQS with trends in seagrass densities.

2.4.1 Trends in seagrass condition

We found statistically significant declines in seagrass density at eight of the study sites, namely; Garden Island Settlement, Southern Flats, Jervoise Bay, Garden Island 3.2 and 5.5 and at the Warnbro Sound 2.0, 3.2 and 5.5m reference sites. This contrasts with Lavery and McMahon (2011) who reported significant declines at the three of the Warnbro Sound reference sites and only at Garden Island Settlement within Cockburn Sound. When using a less conservative test that has an 80% chance of not having occurred by chance (p = 0.2), we found declines in seagrass density at 15 of the study sites (Table 1).

While a decline in seagrass density is worrying, the patterns are similar in both impact and reference sites, thus, it appears that there is a general, broad-scale decline in seagrass density across the area, and that is not linked to any single anthropogenic pressure as measured and analysed in this study (see Chapter 4).

The Garden Island Settlement, Luscombe Bay and Bird Island sites all had significantly lower mean densities of seagrass than their respective reference sites as well as declining trends in density. These sites are of most concern to the program, as under a scenario where seagrass is declining at the reference sites, losses at these sites may be overlooked if seagrass densities at the reference sites continue to decline.

Of particular concern for the protection of seagrasses in Cockburn Sound, is the fact that significant declines were detected in three of the Warnbro Sound reference sites, and weaker trends (significant at α = 0.2) were found in the remaining reference sites. These declines may mask similar decreases in impact sites as the trigger values used for assessment against the EQS would also be declining and would, therefore, reduce protection of seagrass in Cockburn Sound. Under the EQS, there is a provision for using default, absolute minimum seagrass density values (Table 1b in Environmental Protection Authority, 2005) where appropriate reference values cannot be calculated. Lavery and McMahon (2011) recommended that seagrass densities at all sites be compared to both calculated percentile reference values and to the default values during annual reporting to protect against the decline of seagrass at the Warnbro Sound reference sites. We support this recommendation, and further suggest that additional reference sites be established, against which, declines at Warnbro Sound can be assessed. The placement of these reference sites should be sufficiently well distributed and distant to Cockburn Sound so as to place changes observed within Cockburn Sound into a regional context. The Western Australian Marine Monitoring Program (WAMMP) within the Department of Parks and Wildlife, has established sites in Marmion Marine Park and in the Shoalwater Islands Marine Park. In addition, several sites were established in the Jurien Bay Marine Park as part of the Cockburn Sound monitoring program and other sites exist in Geographe Bay which have all been established using the same standard protocols as the Cockburn Sound sites (see Appendix 4). Thus some data from other locations does exist and may be used for gauging changes in Cockburn Sound over time.

2.4.2 Bathymetry

While most sites were very similar to the original measured depths, several (Southern Flats, Bird Island, Mersey Point and Garden Island 7.0m) were found to be different to those that were originally assigned. For the most part, these can easily be rectified by comparing them to the more appropriate reference sites, and in most cases these discrepancies would have little effect on data interpretation under the EQS guidelines (Lavery and McMahon, 2011). This was supported by the repeated measures ANOVAs reported here which found very similar patterns when impact sites were compared against multiple reference sites. However, to properly gauge the implications of such a shift, a retrospective analysis of median values from the impact sites against percentiles from the new reference sites would be necessary to properly inform on the condition of seagrass under the EQS guidelines.

Of greatest concern is the Garden Island 7.0m site which has previously been measured as 6.5m (Lavery and McMahon, 2011) but may be as shallow as 5.79m. This site is most likely to show changes in seagrass density due to reduced light availability and may provide an early indication of changes in water quality. However, the difference in light availability between this site and the deep reference site may be significant. This site should, therefore, be assessed against the Warnbro Sound 5.5m site rather than the Warnbro Sound 7.0m site that it has historically been compared to. There are several options to consider here to rectify this issue. Firstly, the Garden Island 7.0m site be re-located further down-slope so it corresponds to the deepest Warnbro Sound reference site (Lavery and McMahon, 2011). This would result in a loss of data from what represents the deepest site in Cockburn Sound, surveyed with the standard, fixed quadrat methodology. The second option is to, in future years, compare this site to the Warnbro Sound 5.5m site, which is a more appropriate reference. This would mean that the Warnbro Sound 7.0m site is superfluous and could be removed from the program. Alternatively, an additional site could be established in 7.0m of water in Cockburn Sound which is equivalent to the deepest reference site. Given that the primary aim of this program is to monitor seagrass health in relation to reductions in light in Cockburn Sound, establishing a deeper site is likely to be the best option.

Another issue that was uncovered by the bathymetry analysis conducted here is that the Warnbro Sound 3.2m reference site is actually closer to 2.5m, meaning there is no true reference site at 3.2m. Five of the impact sites have historically been compared to this reference site, and while reference sites were established to approximate the depths of the monitoring sites (Lavery and McMahon, 2011), most of these sites are between 0.5-1.0m deeper than the measured depth of the Warnbro Sound 3.2m reference site.

Changes in seagrass density at impact sites will be more readily detected if they are compared to a shallower reference site, so this currently represents a more conservative approach. In contrast, the Mersey Point site is ~0.5m shallower than the measured depth of the Warnbro Sound 3.2m reference site and should be compared to a more appropriate reference.

3 Characterising the pressures on seagrasses in Cockburn and Warnbro sounds

The objective of any monitoring program is to detect changes in the condition of the asset of interest, above natural patterns of spatial and temporal variation, and to identify the causes of any change in condition. The identification of human pressure, negatively impacting condition, should elicit a management response to, as far as possible, reduce or remove the pressure until such time as the condition of the asset returns to its 'normal' state. In order to do this effectively, the pressures acting on the asset need to be identified and measured in a systematic way across both reference and impacted sites. Assessing the range of pressures at a site level allows the pressure or the suite of pressures responsible for any changes in asset condition, to be pinpointed. For example, if water temperature is not different between impact and reference sites, then it can likely be discounted as causing a decline in condition at an impacted site. Thus, when a decline in condition is detected, the pressures can be assessed to determine which have changed at the site of interest and management interventions can be initiated (OECD, 1993).

Cockburn Sound is a heavily industrialised area, which contains an oil refinery and a range of other industries including; waste water treatment, fertiliser manufacturers, iron, steel, alumina and nickel refineries, a grain export terminal, a power station and a number of tanneries. The growth of industry in the area has also lead to significant modifications of the coast and circulation of the bay due to construction of wharves, breakwaters and the dredging of shipping channels. Between 1973 and 1976, a causeway was erected from Garden Island to the mainland to facilitate a naval base. The causeway was calculated to have caused a 40% reduction in circulation in the southern sound (Cockburn Sound Management Council, 2005).

Increased environmental concern, following nutrient enrichment and dieback of seagrass in Cockburn Sound, led to a number of environmental studies and water quality monitoring, and for over 20 years, summer water quality monitoring has been undertaken at a number of sites in Cockburn and Warnbro sounds. Water quality monitoring has shown that nutrient levels have declined significantly since the 1970s, and there have also been marked improvements in light attenuation and chlorophyll *a* concentrations (Wienczugow et al., 2009). In addition, there have been significant declines in both sediment and water column contaminant concentrations (Bourke and Chase, 2009; Department of Water, 2006).

Here, we used water quality data from sites that were in close proximity to seagrass monitoring sites across Cockburn and Warnbro sounds, in order to characterise the pressures on seagrass communities in the area. Where no current or recent data were available for a pressure, we used qualitative data or reviewed literature to help characterise each seagrass site. Specifically, we:

1) examined long term trends in water quality parameters;
2) collected and reviewed qualitative information; and,
3) characterised the likely pressures on seagrass communities at various sites across Cockburn and Warnbro sounds.

3.1 Review of pressures on seagrass communities in Cockburn Sound

Seagrass beds are among the most valuable and threatened of marine habitats (Duarte, 2002) and globally, seagrass losses are estimated to be around 7% yr^{-1}; a rate which is comparable to losses of mangroves, coral reefs, and tropical rainforests (Waycott et al., 2009). These losses are a consequence of natural and anthropogenic pressures acting over a range of spatial and temporal scales. In this context, natural pressures are those environmental characteristics that drive variation in seagrass communities under 'undisturbed' conditions (e.g. cyclones and sedimentation), while anthropogenic pressures are the human influences that directly or indirectly result in an environment changing (e.g. anchoring, terrestrial run-off, dredging etc; Simpson and Friedman, n.d., unpublished). In addition to these pressures, climate change (elevated sea temperature, storminess, sea level rise etc.) is a major emerging threat (Poloczanska et al., 2007) which may influence seagrasses over broader spatial and temporal scales than most other anthropogenic pressures. Although efforts are being made to conserve and restore seagrass systems (e.g. Statton et al., 2012) there are still major gaps in the understanding of stress tolerance in seagrasses (Borum et al., 2005). Here we briefly review the important natural, anthropogenic and climate change pressures on seagrasses (Table 4) and examine how they influence seagrass communities within Cockburn Sound.

3.1.1 Light and turbidity

Light is vital for the survival of seagrass and a reduction in light as a result of turbidity and suspended particles in the water column can have rapid and detrimental effect on seagrass health (McMahon et al., 2011; Ralph et al., 2007). Seagrasses have relatively high light requirements (Hemminga and Duarte, 2000) and the distribution of seagrass is restricted to those depths where water clarity is sufficient to allow adequate light penetration. Seagrasses require sufficient light to make enough carbohydrates to meet their growth and respiration requirements (Ralph et al., 2007). The depth to which seagrass grows is at least partly determined by the amount of light it receives, and on average, seagrasses require approximately 11% of surface irradiance to survive (Duarte, 1991). Light reduction is the most important factor contributing to seagrass declines (Hemminga and Duarte, 2000) and declines around the world are generally attributed to reduced light intensity due to sedimentation and elevated suspended material from dredging activities and/or increased epiphyte and phytoplankton growth from nutrient enrichment (Duarte, 2002; Hemminga and Duarte, 2000; Ralph et al., 2007).

Table 4 – Table of the pressures relevant to seagrass communities in Cockburn and Warnbro sounds and the sources of data used for this report.

	Pressure	Scale of impact	Indicator	Data sources for this report
Natural pressures	Storms and sediment drift	localised	Wave and water movement	CSIRO modelled data
	Predation	localised	Abundances of predators	Bancroft (1992), Cambridge et al. (1986)
	Disease and invasions	??	???	No data
	Salinity changes	Broad	Salinity	CSMC long term water quality monitoring program
Anthropogenic Pressures	Coastal development & dredging	localised	Turbidity, nutrients, siltation	CSMC long term water quality monitoring program
	Nutrients and eutrophication	Broad/localised	Chlorophyll a, nutrients, DO	CSMC long term water quality monitoring program
	Boating	localised	Anchor or mooring damage	Department of Transport
	Aquaculture	localised	Turbidity and nutrients	CSMC long term water quality monitoring program
Climate change Pressure	Temperature	Broad	Temperature	CSMC long term water quality monitoring program
	Increasing storms	Broad	Increasing frequency	No data
	Sea level rise	Broad		No data

3.1.2 Nutrients

The availability of nutrients (in particular nitrogen and phosphorus; see methods 3.2.1) is an important factor controlling production of seagrasses (Leoni et al., 2008). Seagrasses are generally nutrient limited and may be expected to display increased growth and productivity during periods of elevated nutrient availability (Hemminga and Duarte, 2000). However, the substantially lower biomass-specific productivity of seagrass over marine macro- and microalgae, does not allow seagrass to compete under eutrophic conditions (Valiela et al., 1997) where the more rapid growth of phytoplankton in the water column and seagrass epiphytes can limit the passage of light to seagrass (Burt et al., 1995). Thus, while increased nutrients do not affect seagrasses directly, the stimulation of increased phytoplankton and epiphyte growth can change a system to being light-limited which can greatly reduce seagrass survival (Hemminga and Duarte, 2000).

3.1.3 Sea Temperature

As temperature significantly affects the biochemical processes involved in photosynthesis and respiration, it is considered a major factor controlling seasonal seagrass growth (Leoni et al., 2008). Seagrass productivity usually exhibits distinct seasonal variations, with rates increasing during spring and summer and decreasing during autumn and winter (Lee et al., 2007; Masini et al., 1995). Water temperature maxima can negatively affect seagrass health and physiology; for example, heat wave conditions (approximately 35 - 40°C) were considered the most likely cause of a sudden dieback of 12,700 ha of intertidal and shallow subtidal seagrasses along 95 km of Spencer Gulf, South Australia in 1993 (Seddon and Cheshire, 2001; Seddon et al., 2000). Prolonged sub-lethal exposure and short-term extreme events are likely to increase in severity and frequency under current climate change scenarios (Diaz-Almela et al., 2007; Rose et al., 2012).

3.1.4 Salinity

Seagrasses are generally tolerant of fluctuations in salinity and have been shown to survive prolonged exposure to both high (65ppt) and low (0ppt) salinity water (Walker and McComb, 1990; Westphalen et al., 2005). Changes in salinity are generally a result of inputs into the environment from outfalls and drains and effects on seagrasses have been shown to be highly localised around point-sources (Westphalen et al., 2005). Since Cockburn and Warnbro Sound are both open to the ocean and are relatively well flushed it is unlikely that seagrasses here will be exposed to large fluctuations in salinity. It is possible that some sites may be exposed to elevated or depressed levels in salinity, in areas of poor circulation (e.g. Mangles Bay) or in areas exposed to terrestrial run-off. While it is unlikely that seagrass in Cockburn Sound is subjected to salinities outside tolerable levels, it is important to understand the effects of potential low-level, chronic changes in salinity, and also to investigate its effect in conjunction with other pressures, (i.e. cumulative effects of multiple pressures).

3.1.5 Storms and Water Movement

Seagrasses tend to exist in shallow, sheltered, soft sediment environments and are susceptible to the effects of storms which can: 1) scour and physically remove large volumes of both above and below-ground biomass, 2) bury large areas of seagrass by shifting sediments; and, 3) cause the formation of ‘blow-outs’ which fragment contiguous habitats and can have very slow recovery rates (Byron and Heck, 2006; Kirkman and Kirkman, 2000; Preen et al., 1995). In addition, storms and cyclones can cause light deprivation in seagrasses by increasing water column turbidity through flooding and the re-suspension of particulate matter from increased wave action (Preen et al., 1995).

In the Perth metropolitan area, swell waves arrive at Perth mainly from the south–south-west in summer and from the west–south-west in winter (Lemm et al., 1999). While wave climate data for Cockburn Sound is largely unavailable, we can roughly rank the seagrass monitoring sites based on modelled swell direction and intensity data (Appendix 2, CSIRO, unpublished data). Under severe storm conditions, Kwinana appears to be the most exposed site, while Mangles Bay and the Garden Island sites are the most protected (Table 5).

During winter, wind-driven water movement plays an important role in the water quality of both Cockburn and Warnbro sounds. Hydrodynamic simulations found that under a

Table 5 – Ranks of wave height from CSIRO modeled mapping. Rank 1 - most exposed/extreme swell to Rank 3 - most protected/lowest swell.

Site	Wave height rank
Carnac (OA9)	2
Coogee (OA10)	2
G.I. Settlement (G2)	3
Kwinana (CB)	1
Luscombe (G3)	3
Mangles Bay (CS11/MB)	3
Southern Flats (SF)	2
Woodman (OA1)	2
Jervoise (CS7)	2
Warnbro (WS4/WSSB)	No data

south-south westerly wind regime water leaving the Peel-Harvey Estuary arrived at Warnbro Sound within two days, and that under a northerly wind regime, water originating from the Swan-Canning Estuary entered Cockburn Sound after 1-2 days (Figure 4; Cary et al., 1995). This results in winter peaks in nutrient concentrations that also coincide with storm driven erosion and sediment disturbance (Johannes et al., 1994; Rule et al., 2012). The combination of these mechanisms leads to increased nutrient loading and intermittent local effects on water quality. The fact that very different circulation patterns, and their associated water quality variability, are influencing Cockburn Sound compared to Warnbro Sound could mean that during winter, seagrass communities at impact sites may be subject to different conditions to the reference sites.

3.1.6 Predation

Grazers may be responsible for seagrass loss through directly ingesting seagrass (e.g. urchins) or indirectly damaging seagrass (e.g. fish) when grazing epiphytic algae and associated invertebrates (Valentine and Heck Jr, 1999). While there are no data concerning recent outbreaks of grazers in Cockburn Sound, several outbreaks of urchins have been previously reported (Bancroft, 1992; Cambridge et al., 1986).

Cambridge (1986) reported that localized aggregations of the urchin *Temnopleuris michaelsenii* had created barrens in seagrass habitat in several sites. The high densities (up to 250 m^{-2}) of urchins at some sites denuded the *Posidonia* canopy and effectively eliminating it from some areas. No *Posidonia* was recorded in these areas even after four years following the infestation (Cambridge et al., 1986). Bancroft (1992) reported densities of *Heliocidaris erythrogramma* of up to 67m^{-2} around Luscombe Bay (Garden Island). This outbreak of urchins caused significant but localised damage to seagrass meadows (Bancroft, 1992). There are no recent data on outbreaks of grazers in Cockburn Sound, and as such this does not currently appear to be a significant pressure on seagrass communities (Langdon et al., 2011).

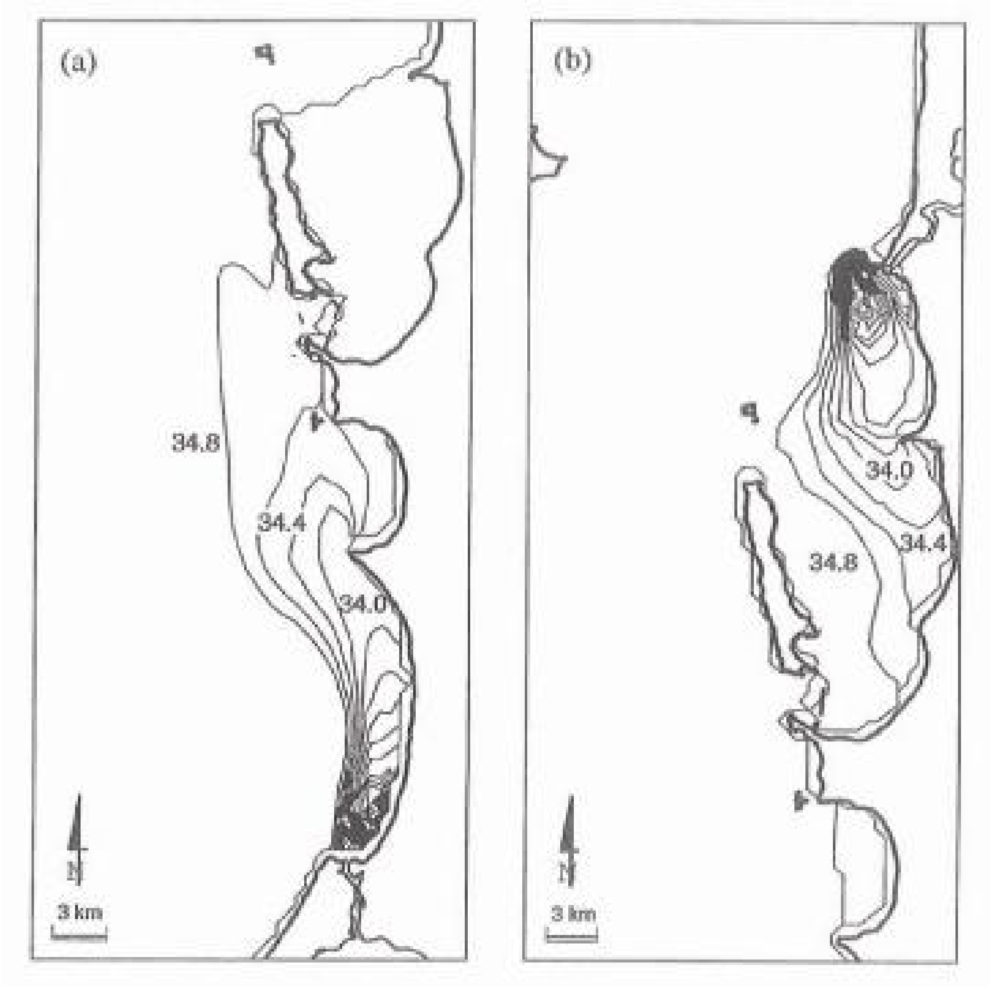


Figure 4– Three dimensional hydrodynamic simulation showing water movement from a) the Peel-Harvey Estuary under a south-west wind at 7.5 m s-1 after 2.5 days and b) the Swan-Canning Estuary under a north wind at 3.5 m s-1 after 2 days. Contours are at 0.2 pss intervals (source: Cary et al., 1995).

3.1.7 Disease and Invasions

Diseases, which are abundant and ubiquitous in seawater, can be considered a natural pressure which influences seagrass communities; however, their impacts are magnified by human activities, changing climate, and other pressures on seagrass (Wernberg et al., 2012). The most notable disease to affect seagrass is “wasting disease” (den Hartog, 1987; Short et al., 1988), which spreads through direct leaf-to-leaf contact. The symptoms spread longitudinally and can cover an entire seagrass shoot in a few weeks. Usually the infections occur on mature leaves (den Hartog, 1987), but during severe infections young leaves may also be affected. The stress of infection reduces photosynthetic activity, which ultimately leads to mortality (Ralph and Short, 2002).

An increase in human transport activities in the recent past has increased the potential for the introduction of non-native flora and fauna (Hoegh-Guldberg and Bruno, 2010). Climate change may also aid the invasion of species in marine systems by, for example, allowing the settlement of non-native warm-climate species into cool systems (Occhipinti-Ambrogi, 2007). Human induced and climatic change-related pressure on seagrass reduces their resistance to invasion. Seaweeds account for some 20% of the known introductions of marine species globally, and have increasingly been implicated in the destruction of seagrass beds, particularly when facilitated by eutrophication, unstable sediments and turbid waters (Thomsen et al., 2012). Introduced invertebrates, particularly epiphytic species, can also have deleterious effects on seagrass photosynthesis and growth; however, few examples of invertebrate invasions in Australia have documented any major effect of seagrass communities (Williams, 2007).

Diseases and invasive species in seagrasses have not previously been reported in Cockburn Sound so it is unlikely to currently be a significant pressure. However, the sound is important to shipping, with many transport vessels sheltering in the Sound for docking and unloading, and there is a high potential for introductions into the area. In addition, sea temperatures appear to be rising (Rose et al., 2012), which may increase the risk of disease outbreaks in the area.

3.1.8 Pollutants and Toxins

While seagrass losses have been widely attributed to coastal developments and industrial inputs, seagrasses are generally highly tolerant of chemical and metal contaminants (Ralph et al., 2010), with few reported losses due to contamination (Hemminga and Duarte, 2000). While Cockburn Sound has had a long history of industrial activity and inputs, the levels of contaminants in both sediments (Department of Water, 2006) and in the water column (Bourke and Chase, 2009) have improved significantly over recent decades and are well below EQS guidelines. Thus, contaminants are unlikely to be a significant source of pressure in Cockburn Sound.

3.1.9 Boating

Destructive boating practices can cause physical fragmentation of seagrass meadows. Probably the most important impact from boating activity is the presence of moorings which produce circular scours in seagrass meadows. Walker et al. (1989) surveyed the damage to seagrass meadows caused by moorings in Cockburn and Warnbro Sounds. A total of 120 moorings were recorded in Cockburn Sound and 66 in Warnbro Sound, with a mean area of scour in both the sounds of 39m^2 per mooring. Swing moorings for larger boats (>8m) resulted in a scoured area of between 176-314m^2 (Walker et al., 1989). The greatest total loss of seagrass (1.8ha) due to moorings was reported from

Mangles Bay, which had the highest concentration of moorings. In Warnbro Sound, the moorings were generally observed between the shore and the 2.0m contour, resulting in a loss of 0.45 ha in this area (Walker et al., 1989). In addition to the direct loss of seagrass cover, scoured patches result in ‘edges’ which are vulnerable to further erosion. Mooring damage in Cockburn and Warnbro Sounds has resulted in an 8.5km increase in the length in the eroding edge of seagrass meadows (Walker et al 1989). The number of moorings has since risen to approximately 480 in the Mangles Bay Mooring Control Area (Department of Transport, 2013), although not all of these are situated on seagrass. With the increasing population in the Perth metropolitan area, this pressure is likely to continue to increase. At present, there is no published data regarding the effects of propeller damage on seagrass in Cockburn and Warnbro Sounds; however, in areas where boating activity is high, and seagrass meadows are shallow (e.g. Mersey Point, Warnbro Sound reference, Southern Flats) this pressure may cause localised seagrass degradation.

3.2 Methods

3.2.1 Data collection

Data from the CSMC water quality monitoring program were collated for the years corresponding to the seagrass monitoring program. Appropriate water quality monitoring sites were selected based on their proximity to the seagrass survey sites (see Chapter 2), and were all < 1.5km from the corresponding seagrass site (Figure 1; Table 6). The only exception to this was the light data at the two Warnbro Sound reference sites; light data are not collected at WSSB, and so light data for this site were taken from WS4. For the purpose of this report, water quality variables were selected if they were known to have some impact on seagrass physiology. Further, only water quality parameters that were consistently collected from most sites and years were used.

Thus the water quality parameters investigated were; salinity, total nitrogen (TN), nitrate/nitrite (NO_x), ammonia (NH_4^+), total phosphorus (TP), orthophosphate (OP), chlorophyll *a* (chl-*a*), dissolved oxygen (DO) , light attenuation (LAC), turbidity, and temperature.

A single sample collected once a week at each site, over the four months of summer (December, January, February, March). Total nitrogen, TP, NH_4^+ and chl-*a* samples were collected using Niskin collectors from the surface, middle and bottom of the water column and combined for a single depth integrated sample (Environmental Protection Authority, 2004). Salinity, temperature, DO, LAC and turbidity were measured *in situ* using a hand-held YSI 6600 multi-parameter at both the surface and bottom of the water column. Only data collected from the bottom of the water column were used in this report as this is most relevant to seagrass health.

Table 6 – List of the sites where seagrass is presently monitored and the corresponding water quality sites monitoring sites chosen for analysis in this report. Note; water quality data were only available 2010-2012 at MB, so CS11 was used for earlier data; also, light attenuation data were not available at WSSB, so data for this parameter only was taken from WS4.

Seagrass monitoring site	Corresponding water quality monitoring site
Carnac Island	OA10
Coogee	OA9
Garden Is. Sett.	G2
Kwinana	CB
Luscombe Bay	G3
Mangles Bay	CS11/MB
Southern Flats	SF
Woodman Point	OA1
Jervoise Bay	CS7
Mersey Point	WSSB/WS4
Garden Is. 2.0m	G3
Garden Is. 2.5m	G3
Garden Is. 3.2m	G3
Garden Is. 5.5m	G3
Garden Is. 7.0m	G3
Warnbro 2.0m	WSSB/WS4
Warnbro 2.5m	WSSB/WS4
Warnbro 3.2m	WSSB/WS4
Warnbro 5.5m	WSSB/WS4
Warnbro 7.0m	WSSB/WS4

3.2.2 Analysis and presentation of pressure data

The 5th, 20th, 80th and 95th percentiles were used as benchmarks for water quality. These were calculated by pooling across both reference sites (WSSB and WS4) and all 11 years (2002-2012). Box plots of the summer water quality data were plotted, and the medians were examined to determine if the benchmark percentiles were exceeded at impact sites for any of the water quality parameters during any year. The number of years where water quality exceeded benchmark values was converted to a percentage; impact sites were flagged if water quality was outside of benchmark levels for more than 30% of sampling times. Conversely, to make a reciprocal assessment for reference sites, the data from all impact sites were pooled and percentiles calculated.

We performed two analyses on water quality data. Firstly, we used a two factor Permutational Analysis of Variance (PERMANOVA) to compare mean values between impact and reference sites. Prior to analysis, all data were checked for homogeneity of variance using Cochran's Test and were appropriately transformed where necessary. Where significant Site x Time interactions were returned, pairwise tests (t tests) between sites within each year were performed.

Next, we investigated long-term trends in mean water quality values at each site by fitting a Generalised Additive Model (GAM) (Wood and Augustin, 2002) using the *mgcv* package in R (R Core Team, 2013; Wood, 2010). For water quality trends, we used α = 0.2 to identify more general trends in data. Where significant trends existed they are presented on the box and whisker plots.

3.3 Results and Interpretations of Pressures

3.3.1 Light and Turbidity

The lowest LAC values were recorded at Warnbro Sound (Table 7), and consequently, most of the impact sites were consistently above the 80 and/or 95th reference benchmarks (Figure 5; Table 7). With the exception of Coogee, all impact sites had significantly higher LAC values compared to the Warnbro Sound reference sites (Figure 5). At Kwinana, Mangles Bay and Jervoise Bay, there was a significant interaction between site and year, meaning that there were differences between the impact and reference sites in ten of the 11 years at Mangles Bay and Jervoise Bay, and six of the 10 years at Kwinana (Table 8).

There were negative trends (p = 0.2) in LAC at Carnac Island, Luscombe Bay and Garden Island settlement; however, the only significant trend (p =0.05) was found at Luscombe Bay (Figure 5).

Table 7 – The percentage of years (2002-2012) where median Light Attenuation (LAC) at each site was above (80/95th percentiles) or below (5/20th percentiles) the range of data at the reference sites. Reference sites were compared to the percentiles of data pooled across all impact sites. Values are presented in bold when water quality was outside of benchmark levels for more than 30% of sampling times. Note; no light data were available at Southern Flats (SF) or Warnbro Sound (WSSB)

	Below		Above	
Site	5th	20th	80th	95th
Carnac (OA9)	0	0	**75**	12.50
Coogee (OA10)	0	0	**100**	**66.67**
G. I. Settlement (G2)	0	0	**63.64**	0
Kwinana (CB)	0	0	**70**	20
Luscombe (G3)	0	0	27.27	0
Mangles Bay (CS11/MB)	0	0	**54.55**	27.27
Southern Flats (SF)	ND	ND	ND	ND
Woodman (OA1)	0	0	**100**	**33.33**
Jervoise (CS7)	0	0	**100**	**72.72**
Warnbro (WS4)	9.09	**81.82**	0	0
Warnbro (WSSB)	ND	ND	ND	ND

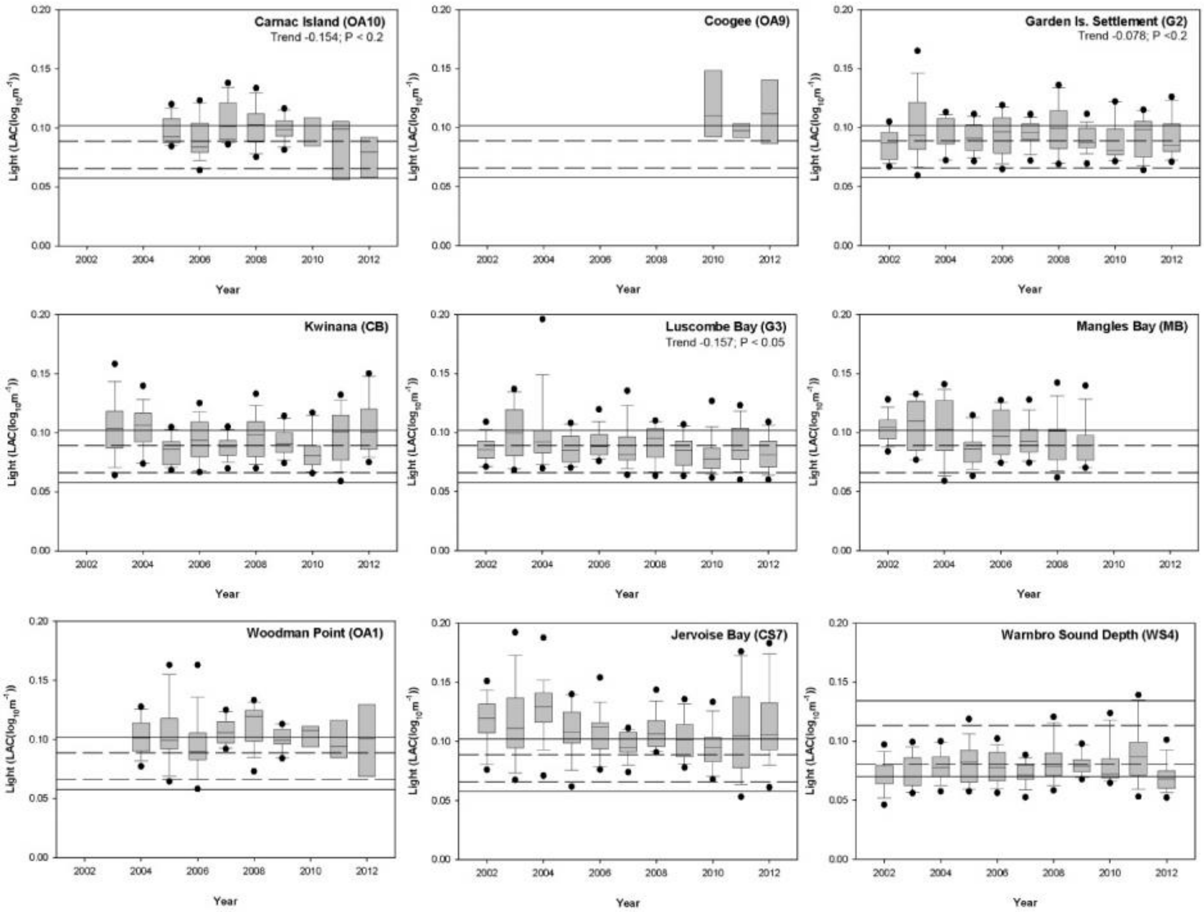


Figure 5: Box and whisker plots of light attenuation (LAC) from 2002-2012 at each site in Cockburn and Warnbro Sound. Lowest whisker – 5th percentile, lower box – 20th percentile, middle box – median, upper box – 80th percentile, upper whisker – 95th percentile, points – outliers. The lines represent the 5th and 95th (solid lines) and 20th and 80th (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). Where a significant trend existed the P value and trend statistics are displayed.

*Table 8 - Comparisons of Light (LAC) between monitoring sites (impact site compared to Warnbro Sound reference site), years and the interaction between site and year using PERMANOVA. Where a significant interaction exists pairwise comparisons of sites between years are presented (ns = no significant difference, * = p < 0.05, ** = p < 0.01, *** = p < 0.001, - missing data).*

	Site (df1)		Year (df10)		Site*Year (df10)		Pairwise comparisons between sites in years										
Site	F	P	F	P	F	P	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Carnac (OA9)	21.36	**0.005**	1.17	0.403	1.77	0.098											
Coogee (OA10)	8.20	0.106	0.15	0.893	2.71	0.07											
G. I. Settlement (G2)	76.33	**0.001**	1.91	0.169	1.09	0.335											
Kwinana (CB)	26.09	**0.001**	0.76	0.672	3.00	**0.003**	-	**	**	ns	**	***	ns	**	ns	ns	***
Luscombe Bay(G3)	23.55	**0.002**	1.30	0.345	1.59	0.093											
Mangles (CS11/MB)	71.82	**0.001**	1.32	0.32	3.64	**0.001**	***	***	***	ns	***	***	**	**	***	***	***
Southern Flats (SF)	ND	ND	ND	ND	ND	ND											
Woodman (OA1)	104.90	**0.001**	1.33	0.327	0.81	0.59											
Jervoise Bay (CS7)	86.45	**0.001**	0.80	0.652	2.59	**0.004**	***	***	***	***	***	***	***	***	*	ns	***

3.3.2 Nutrients

3.3.2.1 Total Nitrogen

In general, Total Nitrogen (TN) concentrations were higher at the Warnbro Sound reference site than in any of the Cockburn Sound sites. Of the impact sites, concentrations of TN were highest at Mangles Bay in four of the 11 years (Table 9) and this site exceeded the 80th percentile reference values in 18% of years. In contrast, no other site exceeded the reference value in any year (Table 9). The higher TN at Mangles Bay is likely to be a result of poor mixing at this site which promotes sedimentation and reduces water quality (Cockburn Sound Management Council, 2009).

Overall, TN concentrations at Kwinana, Garden Island Settlement, Coogee and Southern Flats were significantly lower than the Warnbro Sound reference sites. At Luscombe Bay TN levels were significantly lower than Warnbro Sound for seven years, but for the last three years Mangles Bay had significantly higher TN levels than the reference sites (Table 10). At Carnac Island, TN levels were significantly lower than at Warnbro Sound in two of the four years of sampling.

Both Warnbro Sound reference sites, Southern Flats, Kwinana, and Jervoise Bay all showed significant (p = 0.2) declines in TN (Figure 6). At p =0.05, only Southern Flats and the two reference sites had significant negative trends.

3.3.2.2 Nitrate-Nitrite

Within each site there was some variability with occasional high measures leading to outliers in the data (Table 9). In 2010 there were very high Nitrate-Nitrite (NO_x) levels at Coogee which drove the median above both the 80th and 95th percentiles (Table 9). The concentration of NO_x was significantly higher at Southern Flats than at the Warnbro Sound reference site. NO_x at Coogee was different to the reference site in each of the year (Site x Year interaction) where data was available (Table 10).

At all the sites except Carnac, Coogee and Woodman Point, which are situated to the north in Owen Anchorage, there was a significant (p = 0.05) negative trend in NO_x concentration (Figure 7). It must be noted; however that these sites all had four or less year's data with which to calculate trends.

3.3.2.3 Ammonium

Mangles Bay recorded the highest Ammonium (NH_4^+) concentrations for four of the last 11 years; however this was still within the bounds set by the percentiles of the reference sites (Table 9). Generally, the concentration of NH_4^+ at the Warnbro Sound reference sites was above the 80th percentile of all the impact sites.

Table 9 – The percentage of years (between 2002-2012) where the median Total Nitrogen, Nitrate-Nitrite, and Ammonia at each site was above (80/95th percentiles) or below (5/20th percentiles) the range of the data at the reference sites. Reference sites were compared to the percentiles of data pooled across all impact sites. Values are presented in bold when water quality was outside of benchmark levels for more than 30% of sampling times.

	Total Nitrogen				Nitrate-Nitrite				Ammonia			
	Below		Above		Below		Above		Below		Above	
Site	5th	20th	80th	95th	5th	20th	80th	95th	5th	20th	80th	95th
Carnac (OA9)	0	11.11	0	0	0	0	25	25	0	0	0	0
Coogee (OA10)	25	**37.50**	0	0	0	0	0	0	0	0	0	0
GIS (G2)	0	**45.45**	0	0	0	0	9.09	0	0	0	0	0
Kwinana (CB)	0	**60**	0	0	0	0	10	0	0	0	0	0
Luscombe (G3)	0	**63.64**	0	0	0	0	0	0	0	0	0	0
Mangles Bay (CS11/MB)	0	9.09	18.18	0	0	0	0	0	0	0	0	0
Southern Flats (SF)	0	**54.55**	0	0	0	0	18.18	9.09	0	0	9.09	0
Woodman (OA1)	0	**33.33**	0	0	0	0	0	0	0	0	0	0
Jervoise (CS7)	0	9.09	0	0	0	0	9.09	0	0	0	0	0
Warnbro (WS4)	0	9.09	0	0	0	0	0	0	0	0	27.27	0
Warnbro (WSSB)	0	18.18	9.09	0	0	0	9.09	0	0	0	**36.36**	0

*Table 10 - Comparisons of a) Total Nitrogen (µg/L), b) Nitrate-Nitrite (µg/L) and c) Ammonia (µg/L) between impact and reference sites, years and the interaction between site and year using PERMANOVA. Where a significant interaction exists pairwise comparisons of sites between years are presented (ns = no significant difference, * = p < 0.05, ** = p < 0.01, *** = p < 0.001, - missing data).*

	Site (df1)		Year (df10)		Site*Year (df10)		Pairwise comparison of sites between years										
Site	F	P	F	P	F	P	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
a) Total Nitrogen																	
Carnac (OA9)	2.32	0.287	3.83	0.128	3.17	**0.021**	-	-	-	-	-	-	**	-	ns	**	ns
Coogee (OA10)	9.30	**0.037**	2.95	0.224	1.68	0.176											
G. I. Settlement (G2)	9.02	**0.013**	25.00	**0.002**	1.64	0.09											
Kwinana (CB)	14.18	**0.004**	26.93	**0.001**	1.37	0.216											
Luscombe Bay(G3)	27.31	**0.003**	15.09	**0.002**	2.14	**0.018**	ns	ns	*	***	***	**	ns	*	**	*	ns
Mangles (CS11/MB)	4.07	0.079	1.63	0.247	16.62	**0.001**	ns	ns	ns	ns	ns	ns	ns	ns	***	***	***
Southern Flats (SF)	9.07	**0.010**	22.40	**0.001**	1.67	0.078											
Woodman (OA1)	2.44	0.199	24.49	0.067	0.30	0.822											
Jervoise Bay (CS7)	1.53	0.256	23.50	**0.001**	1.47	0.143											
b) Nitrate-Nitrite																	
Carnac (OA9)	1.34	0.453	11.72	0.106	0.05	0.965											
Coogee (OA10)	7.58	**0.028**	0.89	0.673	8.96	**0.003**	-	-	-	-	-	-	**	-	**	**	***
G. I. Settlement (G2)	0.61	0.478	197.64	**0.001**	0.55	0.835											
Kwinana (CB)	0.42	0.524	106.87	**0.001**	1.29	0.262											
Luscombe Bay(G3)	1.59	0.24	377.52	**0.001**	0.38	0.948											
Mangles (CS11/MB)	1.65	0.236	74.22	**0.001**	1.60	0.096											
Southern Flats (SF)	49.97	**0.001**	49.05	**0.001**	1.66	0.088											
Woodman (OA1)	0.54	0.488	0.87	0.56	0.55	0.533											
Jervoise Bay (CS7)	0.04	0.829	147.07	**0.001**	1.04	0.401											
c) Ammonia																	
Carnac (OA9)	2.57	0.249	0.42	0.74	0.80	0.371											
Coogee (OA10)	4.01	0.151	12.21	**0.045**	0.07	0.937											
G. I. Settlement (G2)	9.27	**0.006**	22.18	**0.001**	0.99	0.443											
Kwinana (CB)	9.80	**0.019**	23.48	**0.001**	0.85	0.547											
Luscombe Bay(G3)	15.80	**0.003**	19.66	**0.001**	1.08	0.362											
Mangles (CS11/MB)	0.36	0.557	9.94	**0.001**	1.90	**0.049**	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	ns
Southern Flats (SF)	9.86	**0.010**	33.43	**0.001**	0.77	0.640											
Woodman (OA1)	3.49	0.189	1.90	0.344	0.31	0.715											
Jervoise Bay (CS7)	9.62	**0.015**	25.61	**0.001**	0.86	0.549											

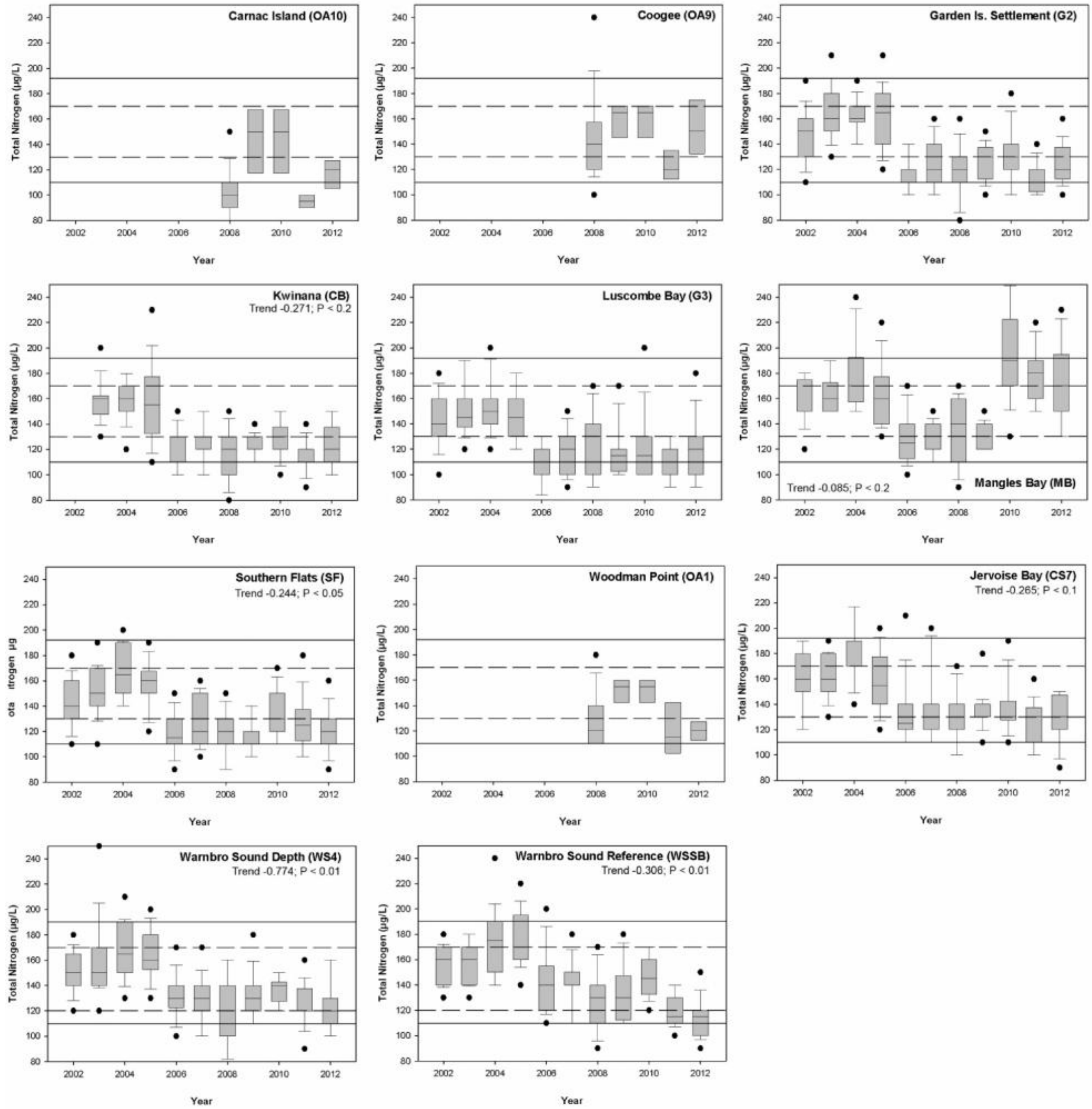


Figure 6: Box and whisker plots of Total Nitrogen (µg/L) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5th percentile, lower box – 20th percentile, middle box – median, upper box – 80th percentile, upper whisker – 95th percentile, points – outliers. The lines represent the 5th and 95th (solid lines) and 20th and 80th (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). Where a significant trend existed the P value and trend statistics are displayed.

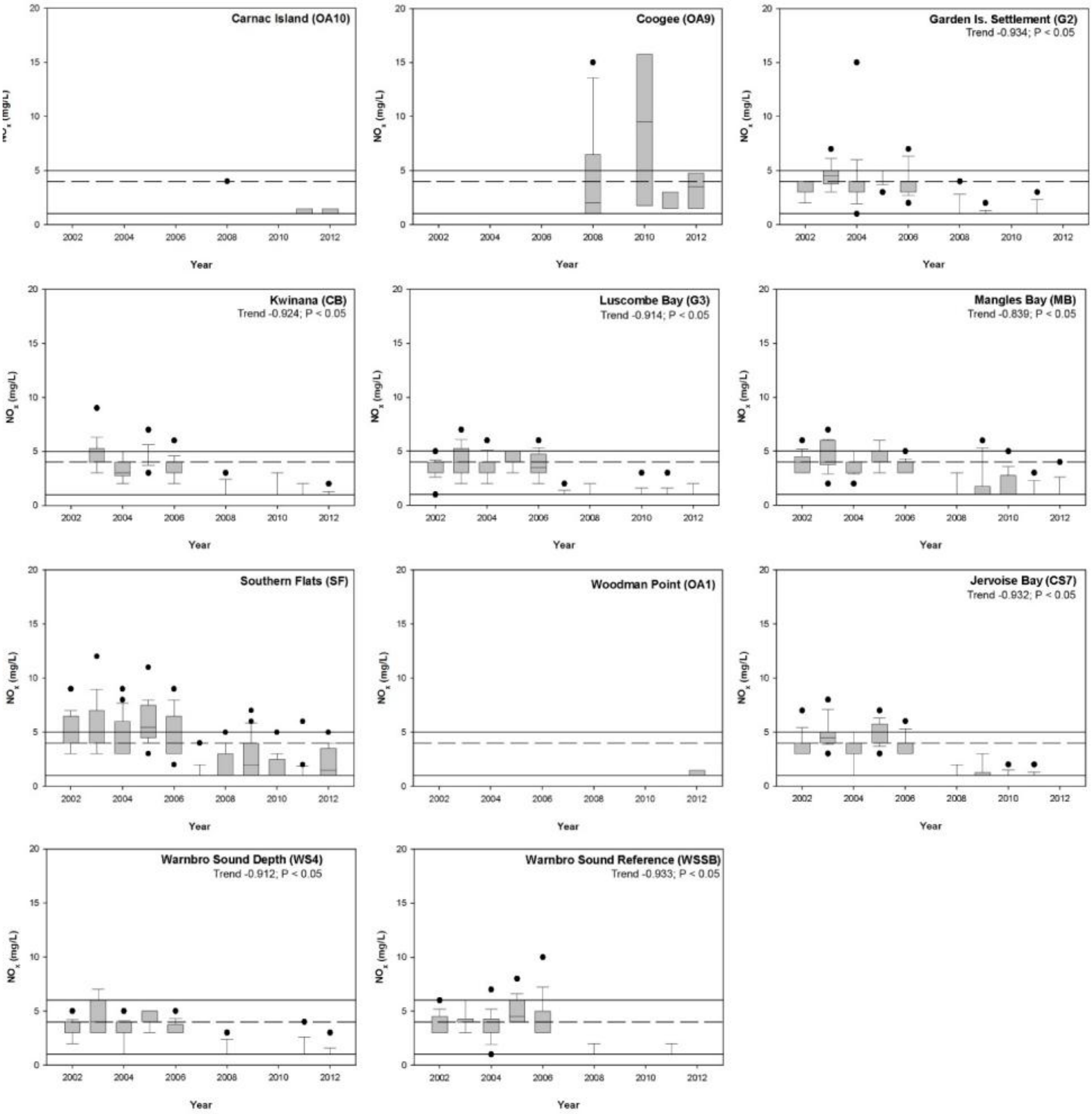


Figure 7: Box and whisker plots of Nitrate-Nitrite (µg/L) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5^{th} percentile, lower box – 20^{th} percentile, middle box – median, upper box – 80^{th} percentile, upper whisker – 95^{th} percentile, points – outliers. The lines represent the 5^{th} and 95^{th} (solid lines) and 20^{th} and 80^{th} (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). In this case, 5^{th} and 20^{th} percentiles are the same value and appear overlaid. Where a significant trend existed the P value and trend statistics are displayed.

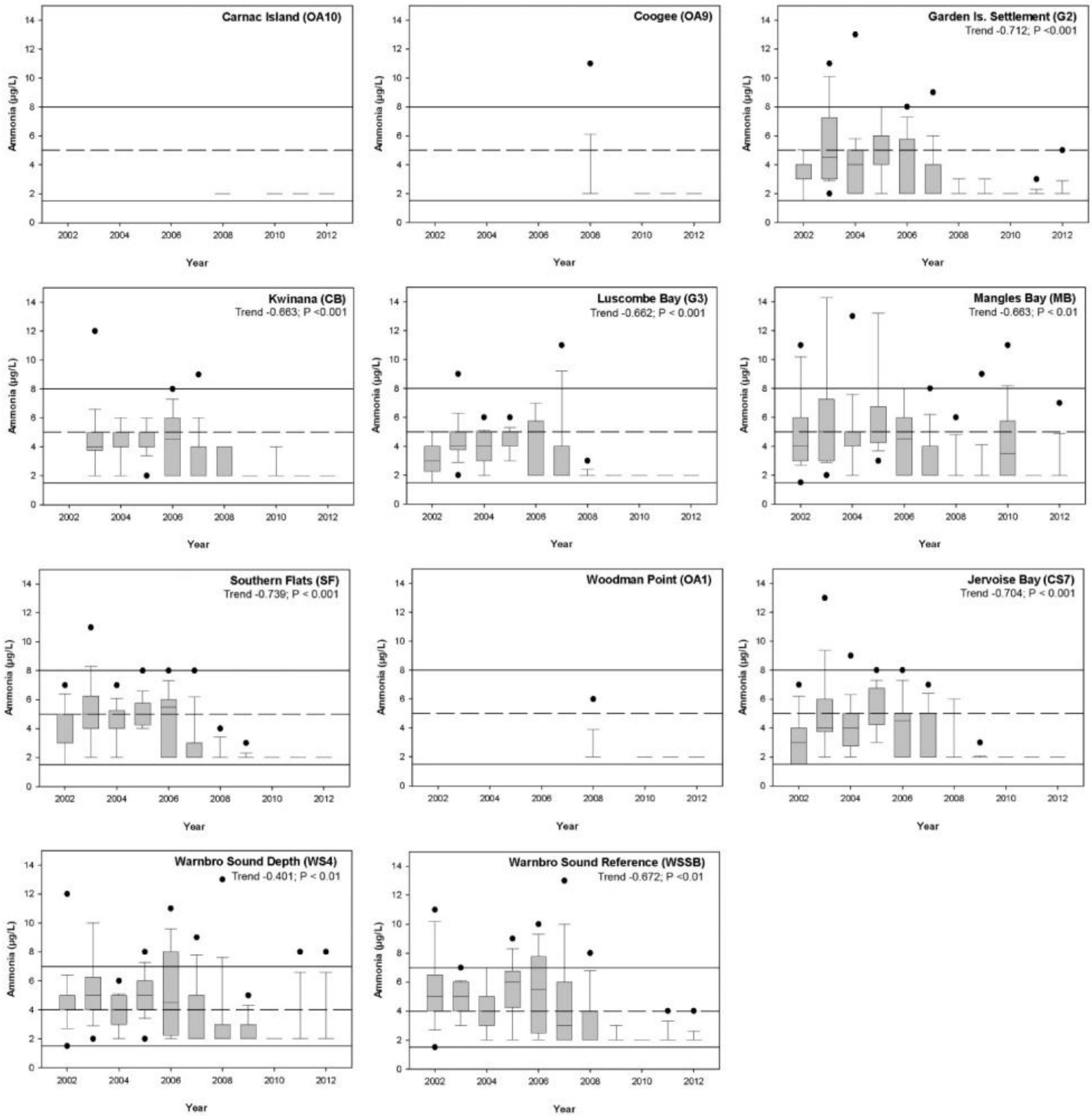


Figure 8: Box and whisker plots of Ammonia (µg/L) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5th percentile, lower box – 20th percentile, middle box – median, upper box – 80th percentile, upper whisker – 95th percentile, points – outliers. The lines represent the 5th and 95th (solid lines) and 20th and 80th (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). In this case, 5th and 20th percentiles are the same value and appear overlaid. Where a significant trend existed the P value and trend statistics are displayed.

Kwinana, Jervoise Bay, Garden Island Settlement, Luscombe Bay and Southern Flats all had significantly lower Ammonia levels to the Warnbro Sound reference sites (Table 10). At Mangles Bay there was a lot of variability in ammonia but this resulted in only one difference between sites (Site x Year interaction) in 2010.

With the exception of Carnac, Coogee and Woodman Point (northern, Owen Anchorage sites), there was a significant ($p = 0.05$) negative trend in NH_4^+ (Figure 8). It must be noted that these all had ≤ 4 yrs data and these results may, therefore, be unreliable.

3.3.2.4 *Total Phosphate*

The majority of sites in Cockburn Sound were below the 20th percentile for most years for Total Phosphate (TP). At both Jervoise Bay and Luscombe Bay, TP levels exceeded the 80th percentile of concentrations in Warnbro Sound in 27% of sampling times, and at Luscombe Bay concentrations exceeded the 95th percentile in 2003 (Figure 9; Table 11). At Kwinana and Southern Flats the 80th percentile was exceeded on 10% and 9% of occasions respectively.

Mangles Bay, Jervoise Bay and Southern Flats all had significantly higher TP concentrations than the Warnbro Sound reference sites; while Kwinana, Woodman Point and Coogee were all significantly lower (Table 12). Two of these sites, Mangles Bay and Southern Flats returned significant interactions. At Mangles Bay there was a significant difference between the sites in all years; however at Southern Flats there was only differences in 2003, 2011 and 2012.

All sites that had >4yrs data displayed significant ($p = 0.05$) negative trends in TP (Figure 9).

3.3.2.5 *Orthophosphate*

The highest Orthophosphate (OP) levels were recorded in both the most southern Cockburn Sound sites, Mangles Bay and Southern Flats, but these rarely exceed the reference benchmark values. For OP the 80th percentile reference values were only exceeded at three sites, and for less than three years (Figure 10; Table 11). Southern Flats exceeded the 95th percentile reference value in 2003.

At six of the impact sites there was a significant interaction for OP concentrations (Table 12). This interaction means that there were some years where the impact and reference sites were significantly different, but generally this only occurred in a small number of the sampling years. All sites were significantly different to the reference sites in 2012.

Of the sites with > 4yrs data, Mangles Bay was the only one to not display a significant negative trend in OP concentrations.

Table 11 – The percentage of years (between 2002-2012) where the median Total Phosphorus and Ortho-Phosphate (µg/L) at each site was above (80/95th percentiles) or below (5/20th percentiles) the range of the data at the reference sites. Reference sites were compared to the percentiles of data pooled across all impact sites. Values are presented in bold when water quality was outside of benchmark levels for more than 30% of sampling times.

	Total Phosphorus				Ortho-Phosphate			
	Below		Above		Below		Above	
Site	5th	20th	80th	95th	5th	20th	80th	95th
Carnac (OA9)	25	**75**	0	0	0	0	0	0
Coogee (OA10)	0	25	0	0	0	0	0	0
G. I. Settlement (G2)	9.09	27.27	0	0	0	0	0	0
Kwinana (CB)	0	30	10	0	0	0	0	0
Luscombe (G3)	0	0	27.27	9.09	0	0	0	0
Mangles Bay (CS11/MB)	0	27.27	0	0	0	0	18.18	0
Southern Flats (SF)		27.27	9.09	0	0	0	27.27	9.09
Woodman (OA1)	0	**50**	0	0	0	0	0	0
Jervoise (CS7)	0	9.09	27.27	0	0	0	0	0
Warnbro (WS4)	9.09	18.18	0	0	0	0	0	0
Warnbro (WSSB)		18.18	0	0	0	0	9.09	0

*Table 12 - Comparisons of a) Total Phosphorus (µg/L) and b) Ortho-Phosphate (µg/L)between monitoring sites (impact site compared to Warnbro Sound reference site), years and the interaction between site and year using PERMANOVA. Where a significant interaction exists pairwise comparisons of sites between years are presented (ns = no significant difference, * = p < 0.05, ** = p < 0.01, *** = p < 0.001, - missing data). Where degrees of freedom do not match the column titles they are included in brackets after the F-statistic.*

	Site (df1)		Year (df10)		Site*Year (df10)		Pairwise comparison of sites between years										
Site	F	P	F	P	F	P	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
a) Total Phosphorus																	
Carnac (OA9)	2.40	0.229	7.58	0.079	1.31	0.285											
Coogee (OA10)	15.85	**0.041**	11.87	**0.037**	0.77	0.52											
G. I. Settlement (G2)	1.07	0.334	410.24	**0.001**	1.86	0.056											
Kwinana (CB)	5.54	**0.035**	640.31	**0.001**	0.98	0.464											
Luscombe Bay(G3)	3.05	0.12	662.64	**0.001**	1.16	0.303											
Mangles (CS11/MB)	28.77	**0.003**	62.73	**0.003**	9.08	**0.001**	**	***	*	***	*	*	**	**	***	***	***
Southern Flats (SF)	5.31	**0.04**	329.92	**0.001**	2.18	**0.012**	ns	*	ns	ns	ns	ns	ns	ns	ns	***	***
Woodman (OA1)	5.21	**0.048**	8.25	0.063	1.02	0.371											
Jervoise Bay (CS7)	46.34	**0.001**	740.34	**0.001**	1.07	0.382											
b) Ortho-Phosphate																	
Carnac (OA9)	8.08	0.078	8.03	0.08	1.51	0.198											
Coogee (OA10)	0.31	0.587	14.33	**0.048**	0.69	0.547											
G. I. Settlement (G2)	0.04	0.856	105.21	**0.001**	3.32	**0.001**	*	ns	*	ns	ns	ns	ns	ns	ns	ns	***
Kwinana (CB)	0.28	0.596	33.22	**0.001**	2.98	**0.002**		*	ns	ns	ns	ns	ns	ns	ns	ns	***
Luscombe Bay(G3)	0.25	0.605	74.25	**0.001**	1.54	0.139											
Mangles (CS11/MB)	7.78	**0.020**	13.93	**0.001**	6.12	**0.001**	ns	ns	ns	***	ns	ns	ns	**	***	ns	***
Southern Flats (SF)	16.64	**0.006**	54.99	**0.001**	1.96	**0.042**	ns	ns	ns	***	ns	ns	*	*	ns	ns	***
Woodman (OA1)	0.19	0.758	19.21	**0.004**	0.48	0.688											
Jervoise Bay (CS7)	1.32	0.296	22.60	**0.001**	4.68	**0.001**	**	***	**	ns	ns	ns	ns	ns	ns	ns	***

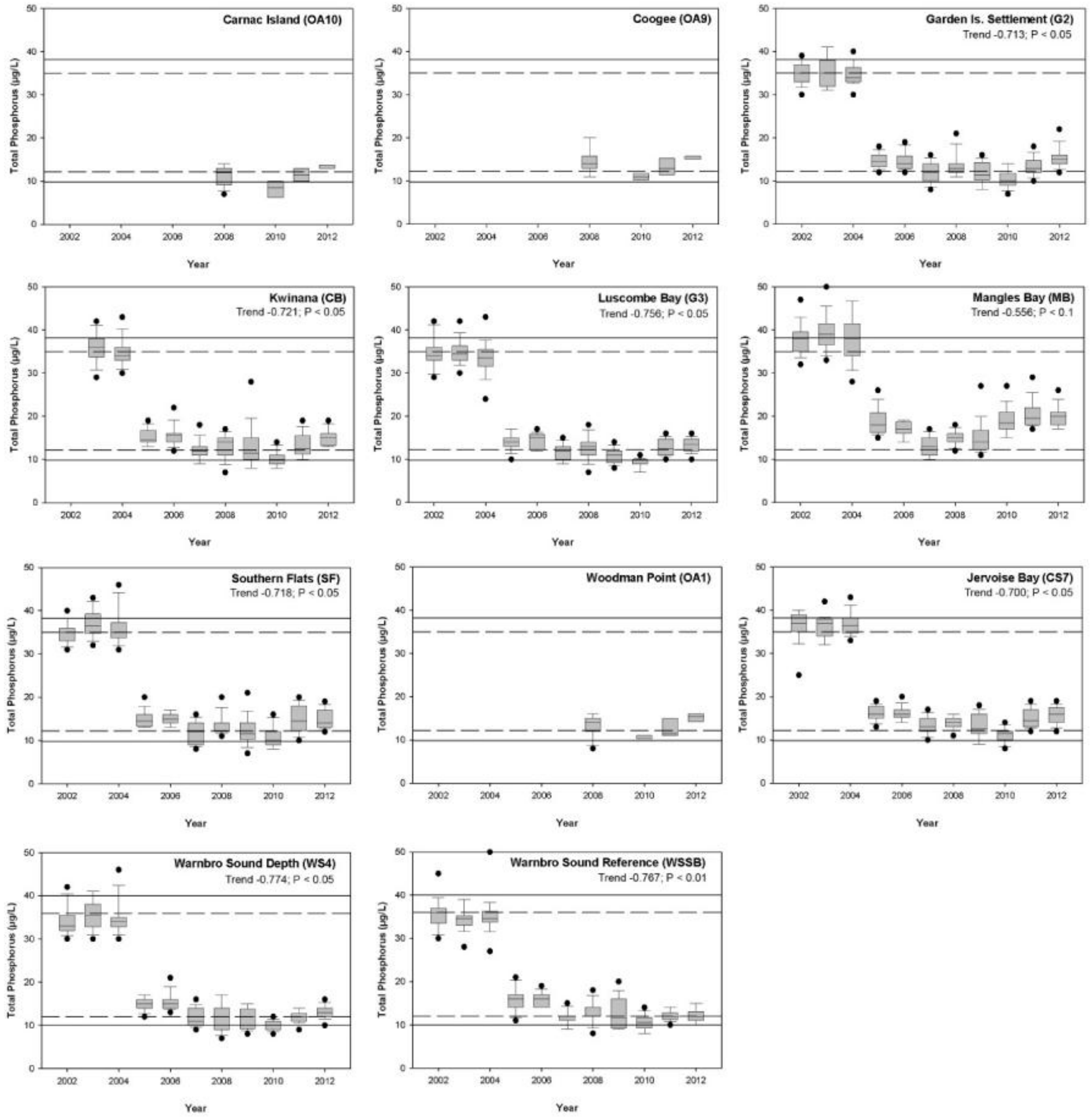


Figure 9: Box and whisker plots of Total Phosphate (µg/L) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5th percentile, lower box – 20th percentile, middle box – median, upper box – 80th percentile, upper whisker – 95th percentile, points – outliers. The lines represent the 5th and 95th (solid lines) and 20th and 80th (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). Where a significant trend existed the P value and trend statistics are displayed.

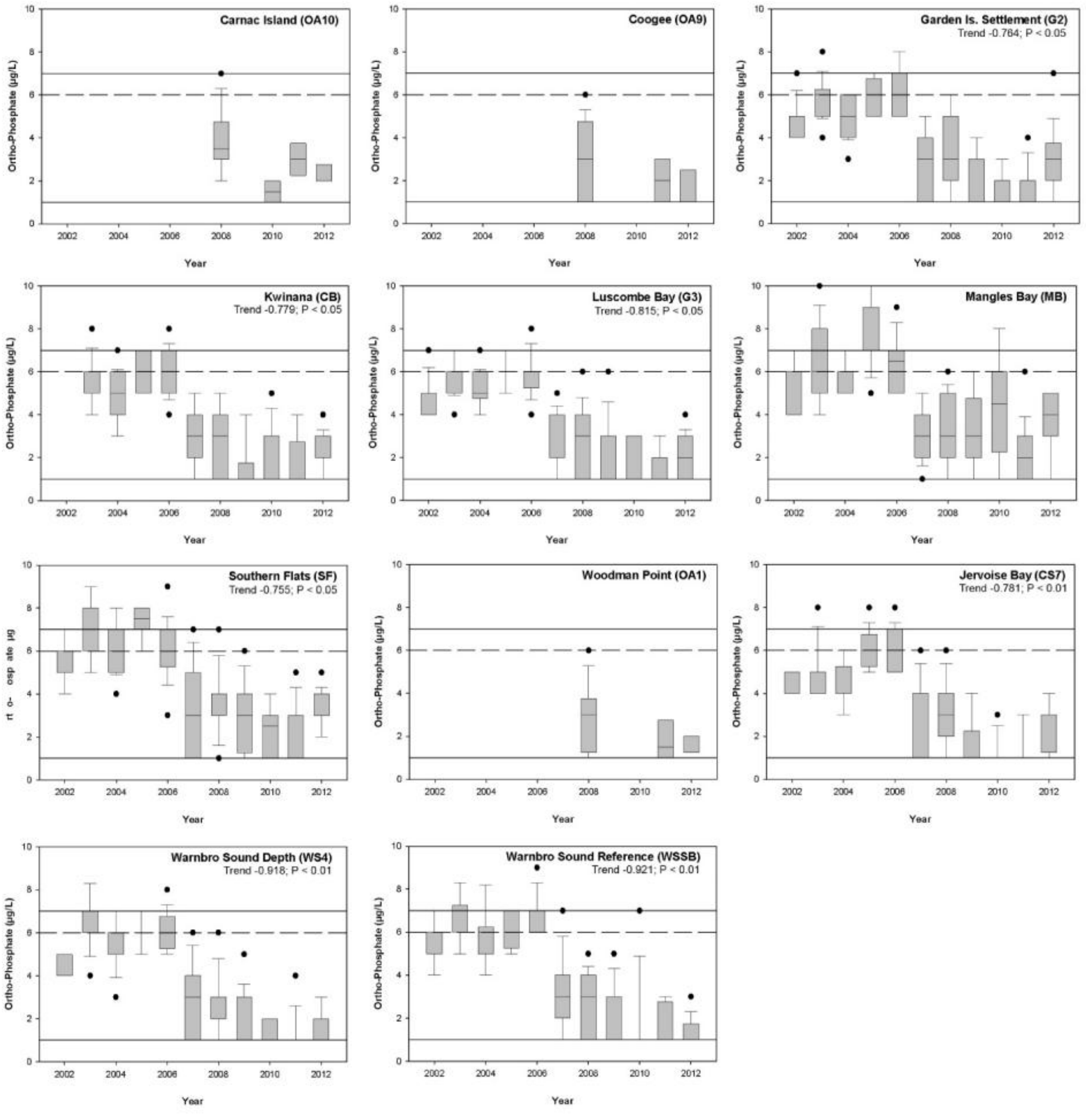


Figure 10: Box and whisker plots of Ortho-Phosphate (µg/L) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5th percentile, lower box – 20th percentile, middle box – median, upper box – 80th percentile, upper whisker – 95th percentile, points – outliers. The lines represent the 5th and 95th (solid lines) and 20th and 80th (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). In this case, 5th and 20th percentiles are the same value and appear overlaid. Where a significant trend existed the P value and trend statistics are displayed.

3.3.2.6 Chlorophyll a

The southern impact sites, Mangles Bay and Southern Flats consistently had the highest Chlorophyll a (chl-*a*) concentrations. With the exception of Carnac Island, all sites exceeded the 80th percentile of chlorophyll concentrations at Warnbro Sound, in at least 22% of years. Coogee, Garden Island Settlement, Mangles Bay, Southern Flats and Jervoise Bay all exceeded the 80th percentile values in at least 30% of the years. Mangles Bay and Jervoise Bay exceeded this benchmark in all years and also occasionally exceeded the 95th percentile benchmark (Figure 11; Table 13).

Almost all impact sites had significantly higher chl-*a* concentrations than the Warnbro Sound reference sites (Table 14). Both Mangles Bay and Jervoise Bay returned significant Site x Year interactions, with all years at Jervoise Bay, and all but 2008 at Mangles Bay, having significantly different chl-*a* concentrations to the reference sites.

Positive trends (p = 0.2) in chl-*a* were found at both reference sites, Carnac Island, Southern Flats and Garden Island Settlement. However, a significant (p = 0.05), positive trend was only found at Carnac Island (Figure 11).

Table 13 – The percentage of years (between 2002-2012) where the median Chlorophyll a (µg/L) at each site was above (80/95th percentiles) or below (5/20th percentiles) the range of the data at the reference sites. Reference sites were compared to the percentiles of data pooled across all impact sites. Values are presented in bold when water quality was outside of benchmark levels for more than 30% of sampling times.

	Below		Above	
Site	5th	20th	80th	95th
Carnac (OA9)	0	0	0	0
Coogee (OA10)	0	0	**55.56**	0
G. I. Settlement (G2)	0	0	**36.36**	0
Kwinana (CB)	0	0	20	0
Luscombe (G3)	0	0	27.27	0
Mangles Bay (CS11/MB)	0	0	**100**	**63.63**
Southern Flats (SF)	0	0	**36.36**	0
Woodman (OA1)	0	0	22.22	0
Jervoise (CS7)	0	0	**100**	27.27
Warnbro (WS4)	0	0	0	0
Warnbro (WSSB)	0	0	0	0

*Table 14 - Comparisons of Chlorophyll 'a' (µg/L) between monitoring sites (impact site compared to Warnbro Sound reference site), years and the interaction between site and year using PERMANOVA. Where a significant interaction exists pairwise comparisons of sites between years are presented (ns = no significant difference, * = p < 0.05, ** = p < 0.01, *** = p < 0.001, - missing data).*

	Site (df1)		Year (df10)		Site*Year (df10)		Pairwise comparisons of sites between years										
Site	F	P	F	P	F	P	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Carnac (OA9)	13.13	**0.005**	1.98	0.206	0.87	0.534											
Coogee (OA10)	27.22	**0.002**	1.21	0.421	1.19	0.27											
G. I. Settlement (G2)	18.80	**0.005**	6.89	**0.003**	0.92	0.511											
Kwinana (CB)	15.14	**0.003**	3.80	**0.031**	1.30	0.221											
Luscombe Bay(G3)	0.29	0.606	6.34	**0.006**	1.15	0.324											
Mangles (CS11/MB)	55.21	**0.001**	1.98	0.085	7.75	**0.001**	***	***	***	***	***	***	***	***	***	***	***
Southern Flats (SF)	7.48	**0.009**	5.31	**0.005**	1.49	0.127											
Woodman (OA1)	1.51	0.274	1.49	0.317	1.25	0.274											
Jervoise Bay (CS7)	55.16	**0.001**	2.04	0.145	3.70	**0.002**	***	***	***	***	***	***	ns	***	**	***	**

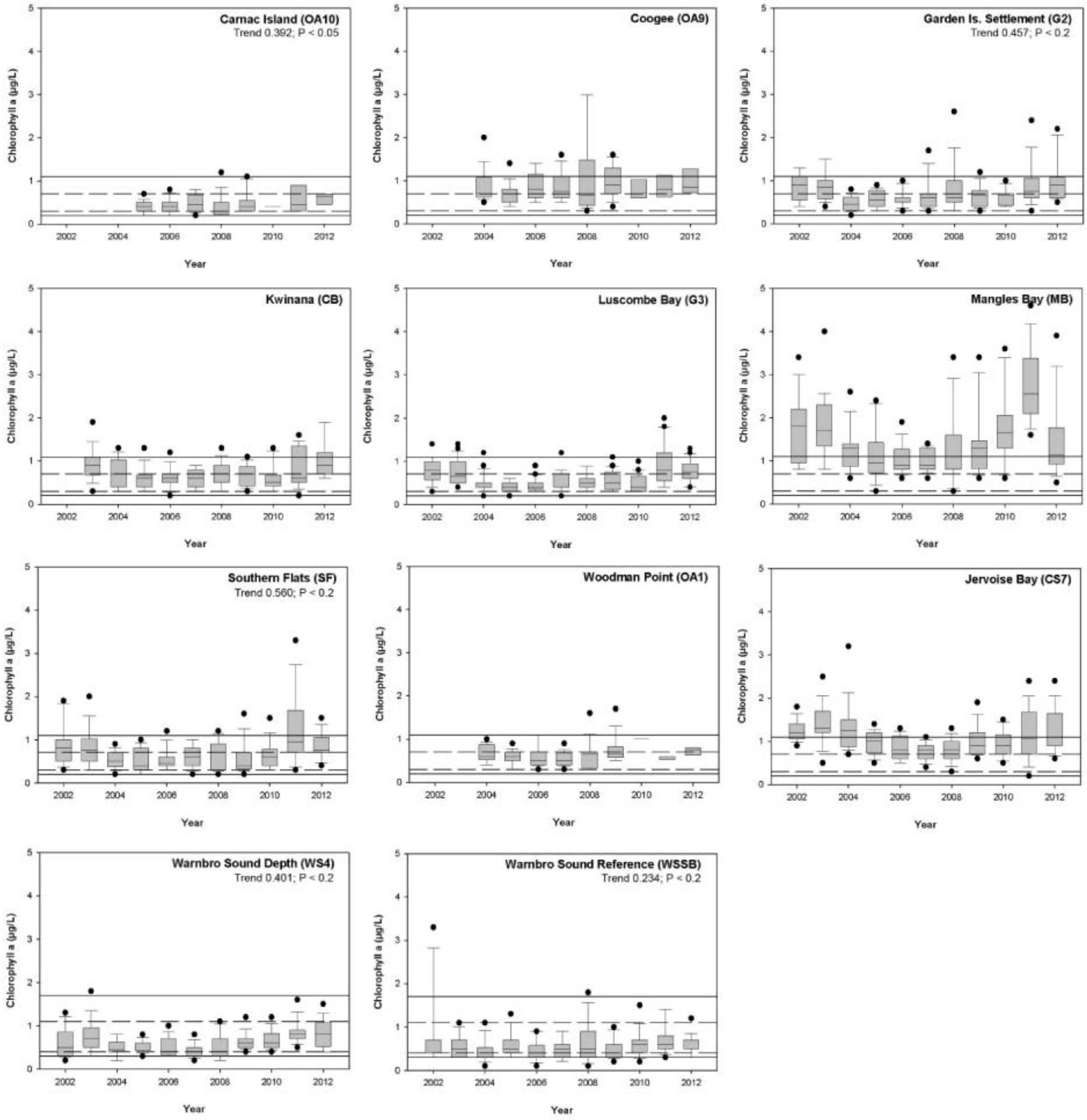


Figure 11: Box and whisker plots of chlorophyll a (µg/L) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5^{th} percentile, lower box – 20^{th} percentile, middle box – median, upper box – 80^{th} percentile, upper whisker – 95^{th} percentile, points – outliers. The lines represent the 5^{th} and 95^{th} (solid lines) and 20^{th} and 80^{th} (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). Where a significant trend existed the P value and trend statistics are displayed.

3.3.2.7 *Dissolved Oxygen*

In general, the Dissolved Oxygen (DO) concentration at Warnbro Sound was higher than in Cockburn Sound, and impact sites were typically within the range of values recorded at the reference site (Figure 12; Table 15).

There were only two sites where DO concentrations were significantly different than the Warnbro Sound reference sites; Mangles Bay was significantly lower while Southern Flats was significantly higher (Table 16). There was a significant interaction between site and year at Southern Flats, with differences in dissolved oxygen between this and the reference site occurring in seven of the 11 years.

Six impact sites and one reference site displayed negative trends (p =0.2) in DO concentrations. Significant (p =0.05) negative trends were only detected at Jervoise Bay one of the Warnbro Sound reference sites (Figure 12).

Table 15 – The percentage of years (between 2002-2012) where the median Dissolved Oxygen (mg/L) at each site was above (80/95th percentiles) or below (5/20th percentiles) the range of the data at the reference sites. Reference sites were compared to the percentiles of data pooled across all impact sites.

	Below		Above	
Site	5th	20th	80th	95th
Carnac (OA9)	0	16.67	0	0
Coogee (OA10)	0	0	0	0
G. I. Settlement (G2)	0	0	9.09	0
Kwinana (CB)	0	0	9.09	0
Luscombe (G3)	0	0	10	0
Mangles Bay (CS11/MB)	0	0	0	0
Southern Flats (SF)	0	0	9.09	0
Woodman (OA1)	0	16.67	0	0
Jervoise (CS7)	0	0	9.09	0
Warnbro (WS4)	0	27.27	9.09	0
Warnbro (WSSB)	0	0	27.27	0

*Table 16 - Comparisons of Dissolved Oxygen (mg/L) between monitoring sites (impact site compared to Warnbro Sound reference site), years and the interaction between site and year using PERMANOVA. Where a significant interaction exists pairwise comparisons of sites between years are presented (ns = no significant difference, * = p < 0.05, ** = p < 0.01, *** = p < 0.001, - missing data).*

	Site (df1)		Year (df10)		Site*Year (df10)		Pairwise comparisons of sites between years										
Site	F	P	F	P	F	P	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Carnac (OA9)	3.40	0.119	4.75	0.077	0.57	0.719											
Coogee (OA10)	2.34	0.187	3.09	0.126	1.14	0.337											
G. I. Settlement (G2)	1.66	0.223	35.14	**0.001**	0.46	0.913											
Kwinana (CB)	0.30	0.616	22.77	**0.001**	0.63	0.781											
Luscombe Bay(G3)	0.66	0.426	22.40	**0.001**	0.69	0.733											
Mangles (CS11/MB)	31.22	**0.003**	18.11	**0.001**	0.68	0.744											
Southern Flats (SF)	21.327	**0.003**	4.1865	**0.017**	1.96	**0.046**	ns	ns	**	***	ns	**	*	***	*	**	ns
Woodman (OA1)	0.08	0.754	2.69	0.153	0.96	0.445											
Jervoise Bay (CS7)	1.83	0.204	9.42	**0.004**	1.68	0.069											

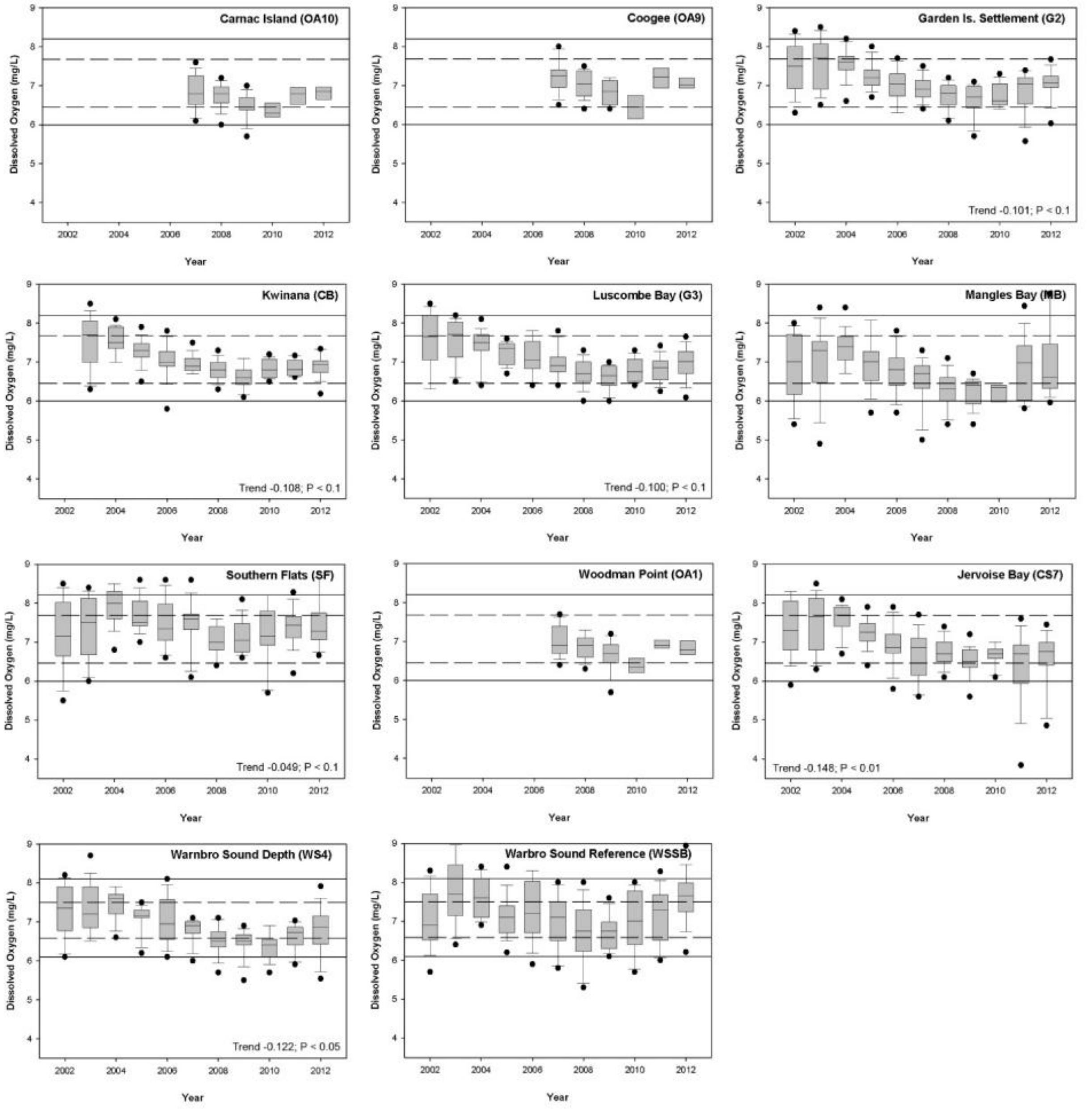


Figure 12: Box and whisker plots of Dissolved Oxygen (mg/L) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5^{th} percentile, lower box – 20^{th} percentile, middle box – median, upper box – 80^{th} percentile, upper whisker – 95^{th} percentile, points – outliers. The lines represent the 5^{th} and 95^{th} (solid lines) and 20^{th} and 80^{th} (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). Where a significant trend existed the P value and trend statistics are displayed.

3.3.3 Temperature

While summer temperatures in Cockburn Sound were generally within the range recorded at in Warnbro Sound (Figure 13; Table 17), the median temperature at most impact sites exceeded the 80th and at some the 95th percentiles in 2011 and 2012. Only Coogee exceeded the 80th percentile benchmark value in more than 30% of years (Table 17). Kwinana, Jervoise Bay, Woodman Point and Southern Flats all had significantly higher temperatures than Warnbro Sound, while Mangles Bay and Coogee were lower (Table 18).

There was a significant positive trend in temperature at all impact and reference sites (Figure 13).

Table 17 – The percentage of years (between 2002-2012) where the median Temperature (^{o}C) at each site was above (80/95th percentiles) or below (5/20th percentiles) the range of the data at the reference sites. Reference sites were compared to the percentiles of data pooled across all impact sites. Values are presented in bold when water quality was outside of benchmark levels for more than 30% of sampling times.

	Below		Above	
Site	5th	20th	80th	95th
Carnac (OA9)	0	0	25	0
Coogee (OA10)	0	0	**33.33**	22.22
G. I. Settlement (G2)	0	0	9.09	0
Kwinana (CB)	0	0	10	0
Luscombe (G3)	0	0	9.09	0
Mangles Bay (CS11/MB)	0	0	0	0
Southern Flats (SF)	0	0	9.09	0
Woodman (OA1)	0	0	22.22	11.11
Jervoise (CS7)	0	0	9.09	0
Warnbro (WS4)	0	0	9.09	0
Warnbro (WSSB)	0	9.09	9.09	0

Table 18 - Comparisons of Temperature (°C) between monitoring sites (impact site compared to Warnbro Sound reference site), years and the interaction between site and year using PERMANOVA.

	Site (df1)		Year (df10)		Site*Year (df10)	
Site	F	P	F	P	F	P
Carnac (OA9)	0.39	0.564	8.42	**0.018**	0.93	0.467
Coogee (OA10)	22.25	**0.001**	10.51	**0.005**	0.65	0.747
G. I. Settlement (G2)	3.97	0.083	40.89	**0.001**	0.23	0.995
Kwinana (CB)	4.54	**0.048**	4.16	**0.021**	0.47	0.884
Luscombe Bay(G3)	1.52	0.271	39.57	**0.001**	0.23	0.994
Mangles (CS11/MB)	30.51	**0.001**	60.58	**0.001**	0.20	0.997
Southern Flats (SF)	6.21	**0.044**	58.17	**0.001**	0.143	1.000
Woodman (OA1)	8.72	**0.007**	11.44	**0.002**	0.66	0.718
Jervoise Bay (CS7)	92.26	**0.001**	164.63	**0.001**	0.05	1.000

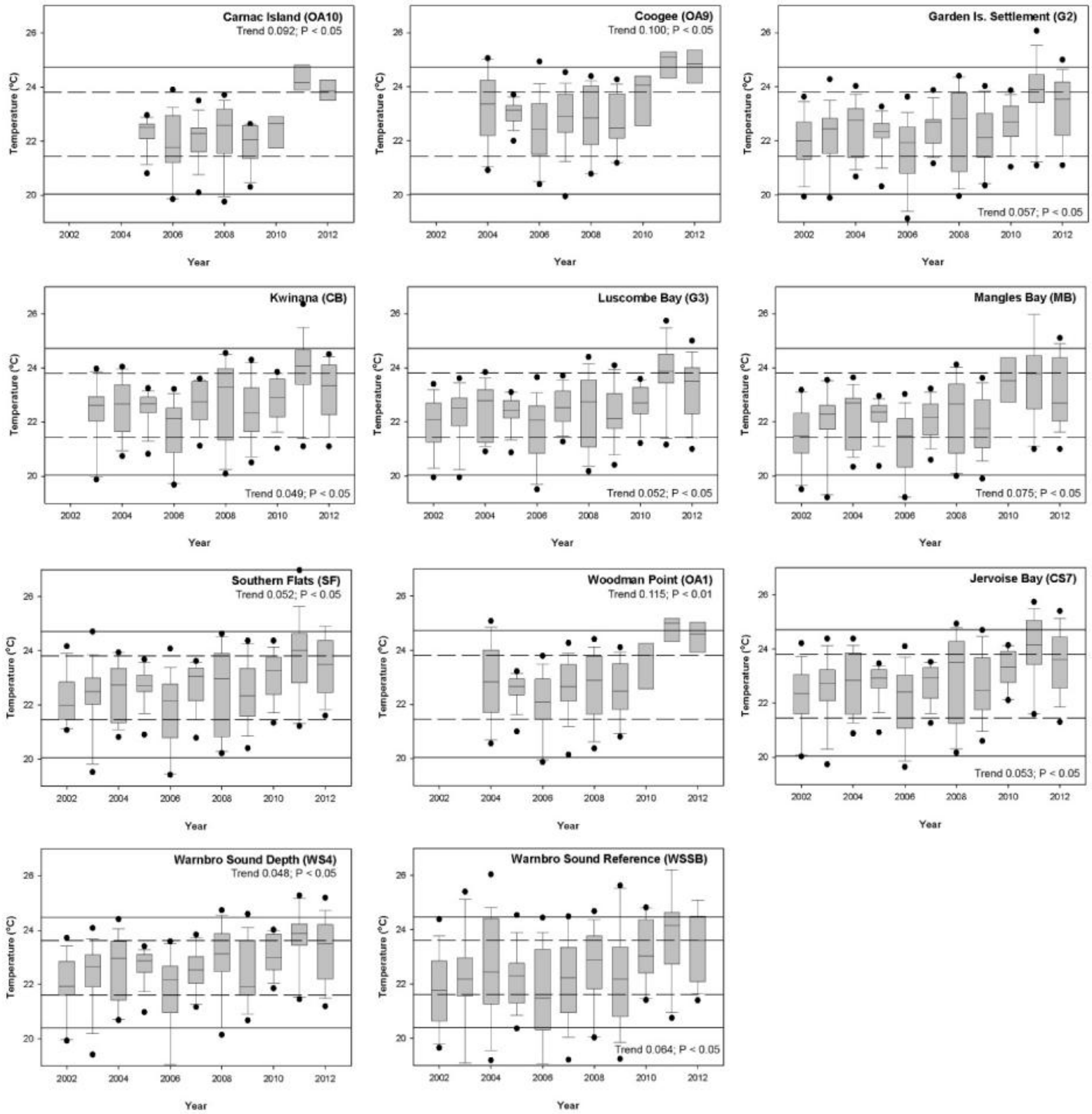


Figure 13: Box and whisker plots of Temperature (°C) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5th percentile, lower box – 20th percentile, middle box – median, upper box – 80th percentile, upper whisker – 95th percentile, points – outliers. The lines represent the 5th and 95th (solid lines) and 20th and 80th (dashed lines) percentiles from the reference sites data (impact sites used for lines for reference site box plots). Where a significant trend existed the P value and trend statistics are displayed.

3.3.4 Salinity

Salinity values are well within normal limits for sea water. Carnac Island consistently had the lowest salinity values, which is most likely a result of being outside of Cockburn Sound and exposed to oceanic conditions. The nearshore sites, Jervoise Bay and Mangles Bay recorded the highest salinity in five years. Despite the variability in salinity around the Sound, the median salinities at all impact sites never exceeded the 95th percentiles of the references sites, while some occasionally exceeded the 80th percentile values (Figure 14; Table 19). There were four impact sites where salinity was significantly lower than their respective reference sites; Garden Island Settlement, Luscombe Bay, Carnac Island, and Southern Flats (Table 20). There was a significant difference in salinity between years at all sites except Kwinana, and no interactions between site and year at any sites, suggesting that, while salinity changed from year to year, it changed consistently within Cockburn Sound and Warnbro Sound.

At $p = 0.2$ all sites except Mangles Bay, Jervoise Bay, Coogee, and Woodman Point revealed negative trends in salinity (Figure 14). However, at $p = 0.05$ significant trends were only observed at the Warnbro Sound reference site and Carnac Island

Table 19 – The percentage of years (between 2002-2012) where the median salinity (ppt) was above (80/95th percentiles) or below (5/20th percentiles) the range of the data at the reference sites. Reference sites were compared to the percentiles of data pooled across all impact sites.

	Below		Above	
Site	5th	20th	80th	95th
Carnac (OA9)	0	12.50	0	0
Coogee (OA10)	0	11.11	0	0
G. I. Settlement (G2)	0	9.09	0	0
Kwinana (CB)	0	10	20	0
Luscombe (G3)	0	9.09	18.18	0
Mangles Bay (CS11/MB)	0	9.09	18.18	0
Southern Flats (SF)	0	9.09	18.18	0
Woodman (OA1)	0	11.11	11.11	0
Jervoise (CS7)	0	9.09	9.09	0
Warnbro (WS4)	0	9.09	18.18	0
Warnbro (WSSB)	0	9.09	18.18	0

Table 20 – Comparisons of Salinity (ppt) between monitoring sites (impact site compared to Warnbro Sound reference site), years and the interaction between site and year using PERMANOVA.

	Site (df1)		Year (df10)		Site*Year (df10)	
Site	F	P	F	P	F	P
Carnac (OA9)	57.86	**0.001**	34.95	**0.002**	0.53	0.821
Coogee (OA10)	6.01	0.054	23.33	**0.001**	0.61	0.769
G. I. Settlement (G2)	13.99	**0.003**	86.38	**0.001**	0.28	0.989
Kwinana (CB)	2.70	0.144	1.93	0.166	0.5	0.816
Luscombe Bay(G3)	44.59	**0.001**	68.12	**0.001**	0.35	0.969
Mangles (CS11/MB)	0.81	0.419	26.74	**0.001**	1.02	0.439
Southern Flats (SF)	5.43	**0.033**	96.06	**0.001**	0.29	0.983
Woodman (OA1)	1.86	0.220	23.58	**0.001**	0.63	0.777
Jervoise Bay (CS7)	0.44	0.517	19.40	**0.001**	1.10	0.368

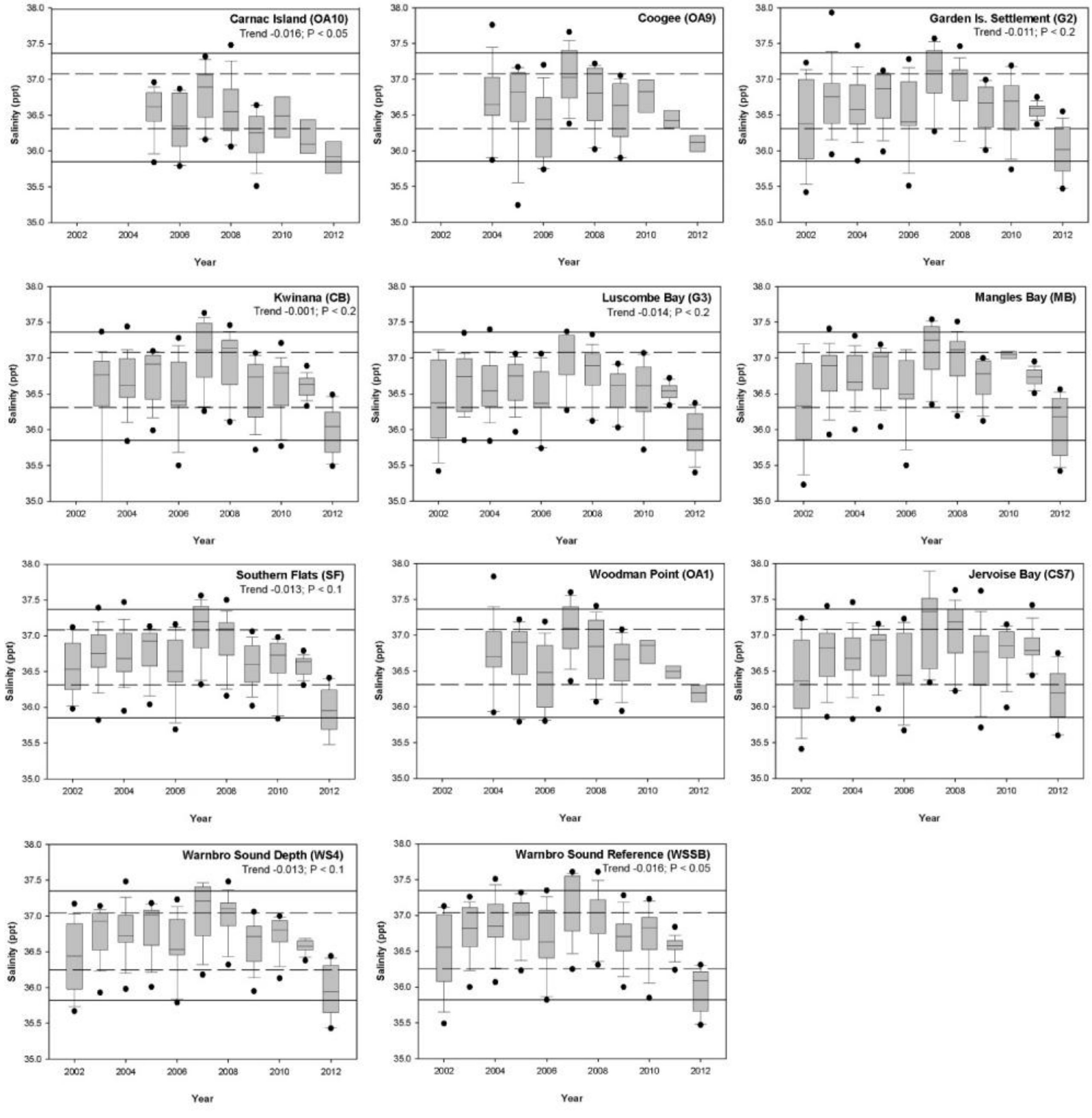


Figure 14: Box and whisker plots of Salinity (ppt) from 2002-2012 at each site in Cockburn and Warnbro Sound which relates to the seagrass collection locations. Lowest whisker – 5th percentile, lower box – 20th percentile, middle box – median, upper box – 80th percentile, upper whisker – 95th percentile, points – outliers. The lines represent the 5th and 95th (solid lines) and 20th and 80th (dashed lines) percentiles from the reference sites data. Where a significant trend existed the p-value and trend statistics are displayed.

3.3.5 Summary of pressures at each site

We used the trend analyses and ANOVA results presented above as well as qualitative data and literature reviews to construct a pressure matrix for each of the seagrass sites in Cockburn and Warnbro sounds (Table 21*).* A site was considered to be under pressure from a specific water quality parameter when: 1) ANOVAs showed a significantly worse condition than that found at reference sites; 2) where there was a trend of worsening water quality; or 3) values at a site were above the 80th percentile (below the 20th percentile for DO) reference values for more than 30% of years. A written summary of these results for each site is presented in Appendix 3.

Table 21 Summary of the significant pressures on each of the Cockburn and Warnbro sounds' seagrass monitoring sites. '+' means that a pressure is recognised at a site.

Pressure	Carnac Island	Coogee	Garden Is. Settlement	Kwinana	Luscombe Bay	Mangles Bay	Southern Flats	Woodman Point	Jervoise Bay	Warnbro Sound Reference
Light and turbidity	+	+	+	+		+	nd	+	+	
Nutrients and water quality										
TN					+	+	+			+
NO_x							+			
NH_4^+										
TP					+	+			+	
OP							+			
Chl-*a*	+	+	+	+	+	+	+	+	+	+
DO			+	+	+		+		+	+
Temperature	+	+	+	+	+	+	+	+	+	+
Salinity										
Disease and invasions	?	?	?	?	?	?	?	?	?	?
Pollutants and toxins										
Wave action and water movement				+						?
Boating (moorings)						+				
Total	3	3	4	5	5	6	6	3	5	4

3.4 Discussion of pressures

Few parameters emerged as being above or outside background levels (as defined by the data collected from reference sites). Although there was some variability in the trends reported here, for the most part, the large number of negative trends suggests that the water quality parameters examined have generally shown some improvement at both reference and impact sites over the past 11 years. The only exceptions to this were for chl-*a* which has increased at half of the sites, DO which has declined, and temperature which has increased significantly across all sites. While these may be an indication of declining water quality, all of the other parameters have improved. It is most likely that these parameters are responding to the significant increase in water temperature, which appears to be a broad-scale change in the area that has affected all of the seagrass monitoring sites. In addition to these, the pressure placed on seagrass habitats from boating, and in particular, moorings, appears to be increasing, and this is an area which requires additional data. Below are presented summaries for each of the parameters measured.

From the analyses presented here it appears that pressure is lowest at the northern-most sites and increases towards the southern end of Cockburn Sound (Figure 15). In particular, Mangles Bay and Southern Flats (southern end of Cockburn Sound) appear to be the monitoring sites under the most pressure from anthropogenic impacts, followed by Luscombe Bay (Garden Island) and Kwinana and Jervoise Bay (eastern side of Cockburn Sound). Mangles Bay and Southern Flats generally have poorer water quality than the other Cockburn Sound sites as a result of restrictions in water circulation near the causeway, which slows water movement and encourages sedimentary and detrital deposition (Cockburn Sound Management Council, 2009).

3.4.1.1 Light and Turbidity

Light levels were generally better (i.e. lower LAC) in Warnbro Sound than in Cockburn sound, and most impact sites had significantly higher LAC values than the reference sites. Despite this, there were negative trends in LAC at Carnac Island, Luscombe Bay and Garden Island Settlement, suggesting that water clarity is improving at these sites.

3.4.1.2 Nutrients

In general, the impact sites had lower mean concentrations of TN, NO_x and NH_4^+ than the Warnbro Sound reference sites and most sites displayed negative trends for these parameters. Of the impact sites, Southern Flats had a significantly higher concentration of NO_x than at the reference site. Concentrations of TN and NH_4^+ were generally highest at Mangles Bay which is likely to be a result of poor mixing at this site (Cockburn Sound Management Council, 2009).

The majority of sites in Cockburn Sound had lower TP and OP levels than the Warnbro Sound reference sites, and almost all sites displayed declines in concentrations for these parameters. Total Phosphorus may still be an issue at Mangles Bay, Luscombe Bay and Southern Flats where levels exceeded the 80th percentile reference benchmark in approximately 30% of sampling times, and occasionally exceeded the 95th percentile benchmark. Concentrations of OP occasionally exceeded the both the 80th and 95th percentile values at Southern Flats.

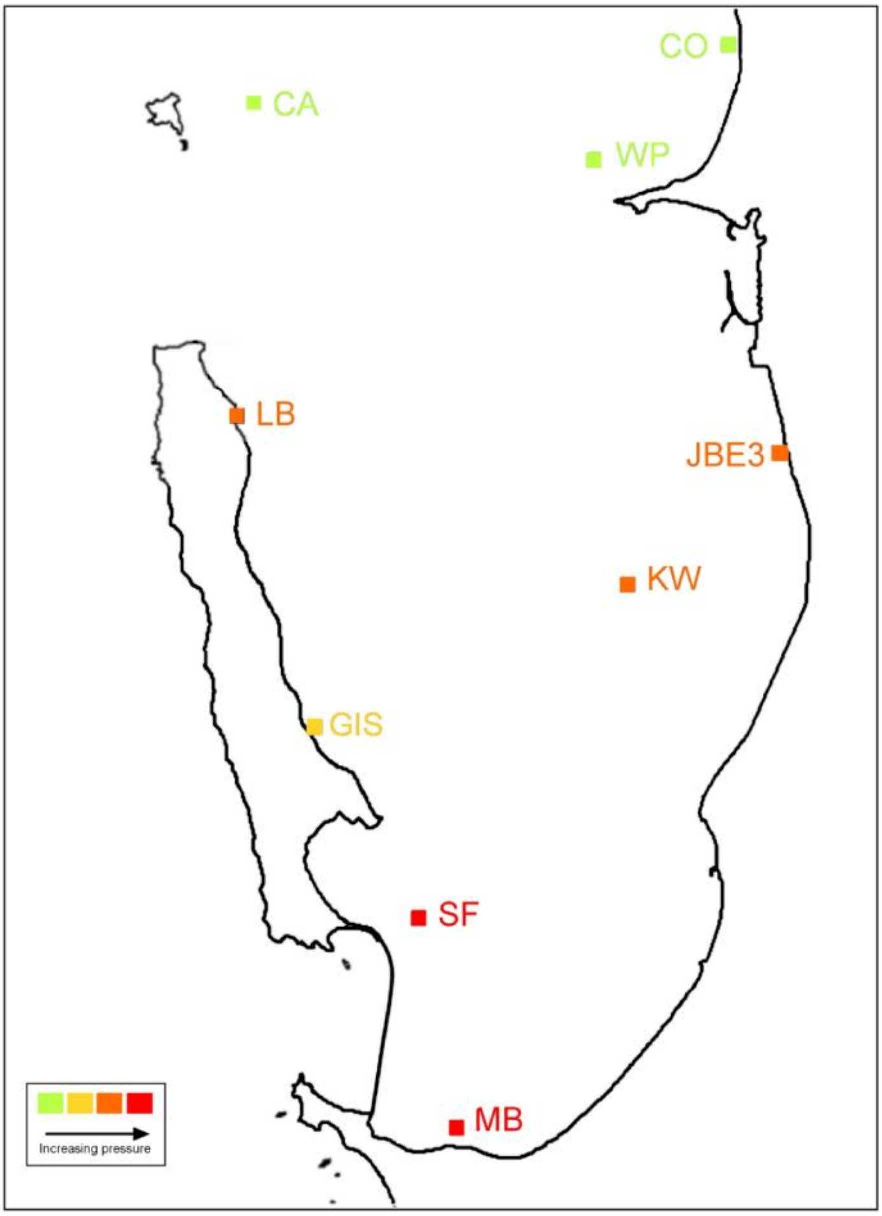


Figure 15 Visual summary of the pressures on seagrass sites in Cockburn Sound, based on the analyses presented in this report.

With the exception of Carnac Island all impact sites exceeded the 80^{th} percentile reference values for chl-*a*. Mangles Bay and Jervoise Bay always exceeded the 80^{th} percentile and often had values above the 95^{th} percentile benchmarks. Increasing trends for Chl-*a* concentration were found at five sites, including both reference sites.

Dissolved Oxygen concentrations at Warnbro Sound were typically higher than in Cockburn Sound; however, Carnac and Woodman Point occasionally fell below the 20^{th} percentile benchmark value. Half of the sites showed declining trends in DO, which could potentially be a result of increasing Chl-*a* concentrations.

3.4.1.3 Temperature

The temperature at all sites has increased significantly over the past 11 years. While summer temperatures in Cockburn Sound were generally within the range recorded in Warnbro Sound, the median temperature at most impact sites occasionally exceeded the 80^{th} percentile. Only Coogee and Woodman Point ever exceeded the 95^{th} percentile benchmark value. Median temperatures at almost all sites exceeded the 80^{th} percentile values in 2011. This was a result of the 2011 heatwave which influenced the entire west coast of Australia (Rose et al., 2012).

3.4.1.4 Salinity

Salinity at a number of sites has declined over the past 11 years. Salinity at most sites was generally well within the range of values recorded at Warnbro Sound. Seagrasses are tolerant of a wide range of salinity (Walker and McComb, 1990; Westphalen et al., 2005). Since both Cockburn and Warnbro sounds are open to the ocean and are relatively well flushed it is unlikely that seagrass here will be exposed to large fluctuations in salinity other than possibly in localised areas with poor circulation. Thus, salinity is unlikely to be a significant pressure on seagrasses in Cockburn Sound.

3.4.1.5 Other pressures

Several other pressures acting on seagrasses have been identified in this report. These include storms and water movement, predation, disease, invasions, pollutants, toxins, and boating. A review of these pressures has been presented above (see sections 2.1.5 to 2.1.9); however, no long-term data has been collected from Cockburn Sound.

4 Linking seagrass condition to water quality

In order to understand the drivers of seagrass decline it is necessary to examine the suite of pressures which are well correlated with patterns in seagrass density. In many cases there are clear links with environmental conditions, for example as nutrients increase and water becomes eutrophic, there may be a decline in seagrass density. However, where pressures are not as extreme, or occur over small spatial scales, impacts may be harder to detect. This may be complicated further by the presence of covarying conditions, or by the additive effects of multiple pressures. It is therefore important to attempt to detect links between patterns in individual pressures but also to investigate the effects of various combinations of pressures.

Here we examined trends in seagrass in relation to the anthropogenic pressures recognised at each site, in order to determine the most likely drivers of observed declines in seagrass density.

4.1 Methods

We used a number of analyses to determine whether water quality parameters were driving seagrass trends. Firstly, we used liner regressions to examine direct relationships between seagrass density at each site and all of the water quality parameters. This was included to identify any parameters which consistently effected seagrass over most or all sites. The large number of comparisons being conducted could potentially result in an unacceptable risk of committing a Type II error (G. Kendrick, pers com), and thus, alpha values were adjusted using a Bonferonni correction (Sokal and Rohlf, 2001). This approach results in a much more conservative test.

Additionally, we fit Generalised additive Models (GAM) using a forward stepwise selection procedure to select significant explanatory water quality parameters for the seagrass density. The choice of the most parsimonious model was based on the Akaike Information Criterion (AIC).

Finally, a Cross-Correlation Function analysis was conducted to compare the time-series of seagrass data and water quality data, and to detect lags in trends between the two datasets. This was done using the *ccf* function in R (R Core Team, 2013). Both seagrass data and water quality data were de-trended prior to analyses by using an ARIMA model. This reduces the risk of detecting spurious correlations because of coincidental trends that may be common to both time series.

4.2 Results

4.2.1 Linear regression

While significant regressions were found at numerous sites and for multiple water quality parameters, there were no parameters which explained trends in seagrass density at all sites. Densities in seagrass over time were most often related to the concentrations of OP, NH_4^+ and NOx (Table 22). At most sites, seagrass densities could not be linked to any parameters.

*Table 22 – Regressions of seagrass densities each year against water quality parameters measured at corresponding sites. Where significant relationships were returned (at $p < 0.005$ following Bonferonni correction), the R^2 values are presented. '-' = p>0.05; *<0.05, **<0.01, ***<0.001). Regressions of NH_4^+, TP, TN, NO_x, and OP at Carnac Island, Coogee and Woodman Point based on only 4 years of data.*

Site	TN	NO_x	NH_4^+	TP	OP	Chl-*a*	DO	LAC	Salinity	Temp
Carnac Island	-	-	-	-	-	-	-	-	-	-
Coogee	-	-	-	-	-	-	-	-	-	-
Garden Is. Sett.	-	-	-	-	-	-	-	-	-	-
Kwinana	-	-	-	-	-	0.785	-	-	-	-
Luscombe Bay	-	-	-	-	-	-	-	-	-	-
Mangles Bay	-	-	-	-	-	-	-	-	-	-
Southern Flats	-	-	-	-	-	-	-	ND	-	-
Woodman Point	-	-	-	-	-	-	-	-	-	-
Jervoise Bay	-	-	-	-	-	-	-	-	-	-
Mersey Point	-	-	-	-	-	-	-	-	-	-
Garden Is. 2.0m	-	-	-	-	-	-	-	-	-	-
Garden Is. 2.5m	-	-	-	-	-	-	-	-	-	-
Garden Is. 3.2m	-	0.791	0.764	-	0.784	-	-	-	-	-
Garden Is. 5.5m	-	0.645	0.661	-	0.657	-	-	-	-	-
Garden Is. 7.0m	-	-	-	-	-	-	-	-	-	-
Warnbro 2.0m	-	-	0.669	-	0.762	-	-	-	-	-
Warnbro 2.5m	-	-	-	-	-	-	-	-	-	-
Warnbro 3.2m	-	-	-	-	-	-	-	-	-	0.813
Warnbro 5.5m	-	-	-	-	0.668	-	-	-	-	-
Warnbro 7.0m	-	-	-	-	-	-	-	-	-	-

4.2.2 Generalised additive model

Generalised additive models were fitted to the seagrass data to examine the additive effects of the various water quality parameters. Trends in seagrass density appear to have little relationship with any of the water quality parameters examined here. No single combination of parameters could explain the decline in seagrass at more than one site (Table 23). There were three sites (Mangles Bay, Jervoise Bay and Garden Island 7.0m) where the best explanatory model contained no parameters. Temperature was a significant parameter at six sites, and LAC, DO and NO_x were significant at five sites. Since there was so little consistency in the models fitted for each site, it is likely that results occurred by chance and the predictive power for future years is probably very low. Alternatively, the measurement of these pressures may not be sufficient to properly capture the nature of the pressure.

Table 23 - The results of the general additive model analysis using 10000 steps. Presented is a star (<0.05, **<0.01, ***<0.001) for each parameter which significantly contributed to the model explaining seagrass density at each site. Limited data were available for Carnac Island, Coogee and Woodman Point, so these sites could not be analysed.*

Site	TN	NO_x	NH_4^+	TP	OP	Chl-*a*	DO	LAC	Salinity	Temp
Garden Is. Sett.				**		*			*	*
Kwinana		*			*	*			*	
Luscombe Bay										*
Mangles Bay										
Southern Flats			*		*					
Jervoise Bay										
Mersey Point						**	**	***	*	
Garden Is. 2.0m		**					**			
Garden Is. 2.5m	*	**	**		**			*		
Garden Is. 3.2m	**						*			
Garden Is. 5.5m	*									
Garden Is. 7.0m										
Warnbro 2.0m	**	**		*			*	*	*	*
Warnbro 2.5m		*			*			*		*
Warnbro 3.2m										**
Warnbro 5.5m										*
Warnbro 7.0m				*		**	*	*		

4.2.3 Cross correlation

The cross correlation analysis investigates relationships between water quality and seagrass trends, and also examines the effects of lags in the explanatory relationship (i.e. water quality in one year may explain seagrass density in the following year) Positive lags occur by chance and should be disregarded. There were some sites where seagrass density could be correlated with water quality (Table 24); however, density at many sites was not correlated to any water quality parameter. Generally, where a relationship existed, seagrass patterns were linked to either the current year's water quality, or the quality of the previous year, but lags were inconsistent across sites. Temperature was the most consistent predictor of seagrass trends, but this parameter still only returned correlations without a lag at five sites.

Table 24 - List of seagrass sites and water quality parameters where a significant cross-correlation was found. Displayed is a numeric value for the number of years lag ('-' = seagrass lags water quality; '+' = water quality lags seagrass) between the trend in seagrass and the trend in water quality. Positive lags occur by chance and should be disregarded. Underlined values indicate a negative correlation. A '0' means that seagrass was correlated to water quality in the same year as water quality sampling (i.e. no lag).

Site	TN	NO_x	NH_4^+	TP	OP	Chl-*a*	DO	LAC	Salinity	Temp
Carnac Island	**0**	**0**		-	**0**	-		-	-	-
Coogee	+1	+1		$\underline{+1}$	$\underline{+1}$	-	$\underline{+1}$		-	-
Garden Is. Sett.	-	-	-	-	-	-	-	-	-	**0**
Kwinana	-	-	-	-	-	**$\underline{0}$**	-	-	**-1**	**$\underline{0}$**
Luscombe Bay	-	-	-	-	-	**$\underline{-4}$**	-	**-2**	**$\underline{0}$**	-
Mangles Bay	-	-	+1	-	-	-	-		-	-
Southern Flats	-	-	-	-	-	-	-		-	-
Woodman Point	-	**0**		-	**$\underline{-1}$**	-	**$\underline{-1}$**	-	-	**$\underline{0}$**
Jervoise Bay	-	-	-	-	-	-	-	-	-	-
Mersey Point	-	**-1**	-	-	-	-	-	**$\underline{-1}$**	-	-
Garden Is. 2.0m	-	-	-	-	-	-	-	-	**-2**	**$\underline{0}$**
Garden Is. 2.5m	-	-	-	-	**0**	-	-	-	**-2**	-
Garden Is. 3.2m	-	-	**-1**	-	-	-	-	-	-	-
Garden Is. 5.5m	$\underline{+1}$	-	-	$\underline{+1}$	-	**$\underline{-1}$**	-	**$\underline{-1}$**	-	-
Garden Is. 7.0m	$\underline{+1}$	-	-	$\underline{+1}$	-	$\underline{+1}$	-	$\underline{+1}$	-	-
Warnbro 2.0m	$\underline{+1}$	-	-	$\underline{+1}$	-	-	-	-	-	-
Warnbro 2.5m	$\underline{+1}$	-	$\underline{+2}$	$\underline{+1}$	-	-	-	-	-	-
Warnbro 3.2m	-	-	**$\underline{-1}$**	-	-	**$\underline{-1}$**	-	-	**-2**	**-2**
Warnbro 5.5m	$\underline{+4}$	-	$\underline{+2}$	$\underline{+4}$	$\underline{+2}$	**-2**	-	-	**$\underline{-3}$**	**$\underline{-3}$**
Warnbro 7.0m	**$\underline{-1}$**	-	-	**$\underline{-1}$**	-	**$\underline{0}$**	-	-	-	**$\underline{0}$**

4.3 Discussion

The water quality parameters examined here do not appear to be driving declines in seagrass in Cockburn or Warnbro sounds. None of the analyses performed revealed any water quality parameters which consistently explained patterns in seagrass density. No parameter could be used to explain seagrass at more than half the sites, and no single combination of parameters explained the seagrass trends at more than one site. This result is not particularly surprising as many of the water quality parameters have shown a general improvement over the past 11 years (see Chapter 2). Declines in seagrass are generally attributed to reductions in light as a consequence of poor water quality (Cambridge et al., 1986; Hemminga and Duarte, 2000), and while the concentration of Chl-*a* has increased at many sites, seagrass declines were not tightly linked this parameter.

Temperature was generally the best explanatory variable in most models; however, this still only explained patterns in seagrass at a small number of sites. Increasing temperatures may be a significant pressure on seagrass communities, as increased temperatures can affect photosynthesis and respiration rates. Optimum photosynthesis rates for *Posidonia sinuosa* are between 18-23°C (Masini and Manning, 1997; Masini et al., 1995). Above these temperatures, *P. sinuosa* requires more light to maintain a positive carbon balance (Masini et al., 1995). Given the significant positive trend in temperature across the study area, pressure on seagrasses from this parameter will continue to increase, potentially leading to further losses of seagrass (Rose et al., 2012). The positive trend in sea temperature has been noted along the temperate WA coastline (Bancroft unpublished data) and seagrass losses in other parts of the state (e.g. Shark Bay) have been linked to these increases in temperature, and to the 2011 marine heatwave event (G. Kendrick, pers. comm.). Thus, it appears that there has been a regional-scale shift in the temperature regime which will continue to impact seagrass communities.

There are several possible explanations for lack of observable relationships found here. Firstly, seagrass declines are linked to anthropogenic or natural pressures which have not been measured. This is unlikely for those pressures acting directly on seagrass (Duarte, 2002; Hemminga and Duarte, 2000) as so many are, or have been, measured in Cockburn Sound. However, the cause-effect pathways of some of these pressures require additional research. For instance, the seagrass monitoring program was established to detect changes in the face of changing water quality conditions which result in phytoplankton blooms and a poorer light environment, While a reduction in Photosynthetically Active Radiation (PAR) causes a noticeable decline in shoot density (e.g. Borum et al., 2005), a loss of PAR is also linked to deoxygenation and increased sulphide toxicity in sediments (Holmer and Kendrick, 2013), which may lead to poorer condition or loss of seagrass. In particular, the effect of generally increasing temperatures and thermal pulse events requires additional research and currently presents a critical knowledge gap for the CSMC program.

Secondly, while the water quality in Cockburn Sound has improved, chronic, long-term exposure to multiple pressures, in combination with generally increasing sea temperatures has not allowed seagrasses to recover in this area, and these effects continue to drive seagrass losses.

Finally, the seagrass monitoring program utilises fixed, permanent quadrats which are surveyed annually. There are two potential issues with this approach. Firstly, *Posidonia* is a clonal organism which grows laterally through rhizome extension and branches from the original point of colonisation (Renton et al., 2011). Given that fixed quadrats have been spaced 0.2-1m apart, it is unlikely that replicates are truly independent of each other, which will confound statistical analyses and their interpretation (Lavery and McMahon, 2011). This can be rectified somewhat by employing randomly cast quadrats (Centre for Marine Futures, 2009) or by increasing the spacing of fixed quadrats (Lavery and McMahon, 2011). Secondly, and more importantly for the CSMC seagrass program, it is possible that the repeated disturbance of these small patches of seagrass is resulting in the mechanical removal of shoots which has not, as yet, been quantified. Thus, seagrass losses at these sites may be an artefact of the sampling procedure. Shoot mortality tends to increase as density declines as shoots become more vulnerable to disturbance by water movement and sediment erosion (Kirkman, 1999).

The fixed quadrat sampling method may be exacerbating the loss of seagrass within measured patches, and may not be representative of condition at a broader scale.

5 Conclusions

Here we examined the long-term trends in seagrass density at two areas with a different history of industrial and port pressures. We found clear and significant declines in seagrass density at many of the long-term monitoring sites in both Cockburn and Warnbro sounds; however, this is in contradiction to the generally improving water quality of the area, which has previously been linked to severe losses of seagrass in Cockburn Sound (Cambridge and McComb, 1984; Cambridge et al., 1986). The general decline in seagrass density is concerning, particularly given the way in which impact sites are assessed against the EQS which means that declines at the reference sites are likely to reduce the power of assessments to detect losses from sites in Cockburn Sound.

Based on the analysis conducted here, we considered Mangles Bay and Southern Flats to be the seagrass sites under the most pressure from anthropogenic impacts, followed by Kwinana, Luscombe Bay and Jervoise Bay. With the exception of Mangles Bay, significant declines in seagrass were found at each of these sites, and at most of the Warnbro Sound reference sites. Thus, there appears to be a general, broad-scale decline in the density of seagrass in the area. It is crucial to better understand how these losses fit into a more regional context and research is needed across the region to provide a framework for understanding the losses in Cockburn and Warnbro Sounds.

Given that most nutrient parameters have improved over the past decade, the most likely explanation for the decline in seagrass is the concomitant increase in water temperature over the same time period. Increasing temperatures may be a significant pressure on seagrass communities, as increased temperatures can affect photosynthesis and respiration rates (Borum et al., 2005). Optimum photosynthesis rates for *Posidonia sinuosa* are between 18-23°C (Masini and Manning, 1997; Masini et al., 1995). Above these temperatures, *P. sinuosa* requires more light to maintain a positive carbon balance (Masini et al., 1995). In addition, thermal events, such as was seen during 2011 (Rose et al., 2012) may dramatically increase shoot mortality rates (Marbà and Duarte, 2010). The effect of generally increasing temperatures and the occurrence of thermal pulse events currently represent a critical knowledge gap for the CSMC program and require additional research. A better understanding of the cause-effect pathway between temperature and seagrass is required to better understand and predict how this pressure will affect seagrass communities in the future.

Previously, Cambridge (1986) suggested that significant declines in seagrass cover could not have been related to broad-scale increases in temperature in the area as similar declines were not seen in areas adjacent to Cockburn Sound. These authors concluded that declines in seagrass were a response to reductions in available light arising from industrial inputs and poor water quality. In the analyses presented here, it appears that water quality has generally improved in both Cockburn and Warnbro sounds. The positive trend in sea temperature has been noted along the temperate WA coastline (Bancroft unpublished data) and seagrass losses in other parts of the state (e.g. Shark Bay) have been linked to these increases in temperature, and to the 2011 marine heatwave event (G. Kendrick, pers. comm.). Thus, it appears that there has been a regional-scale shift in temperature which will continue to impact seagrass communities. The remnant population of seagrass in Cockburn Sound has not been able to expand since its initial rapid decline as *P. sinuosa* colonisation from seedlings and rhizome spread into un-vegetated habitats is extremely slow (Kendrick et al., 2002; Kirkman and Kuo, 1990). Thus, while initial seagrass losses were a result of poor water quality, the combination of low recruitment rates and a shift in temperature across the region continue to force seagrass decline.

Additional surveys at locations outside of Cockburn and Warnbro sounds are needed to properly establish whether the declines reported here are confined to Cockburn Sound or if they represent more general regional-scale losses.

5.1 Recommendations

The aims of this project were to: 1) identify the relevant anthropogenic pressures which are acting on seagrass communities in Cockburn and Warnbro sounds; 2) characterise long-term monitoring sites in terms of these pressures; 3) examine long term trends in seagrass density; 4) link patterns in seagrass density to the identified pressures; and 5) make recommendations to improve the Cockburn Sound seagrass monitoring program. While each of these has been accomplished, we have identified a number of areas where additional data or actions are required.

While we believe that the major pressures acting directly on seagrasses in Cockburn Sound have been identified, there are areas which require additional data and understanding to properly quantify the level of pressure.

The most likely explanation for the decline in seagrass is the broad-scale increase in water temperature across the region which has been linked to losses in other locations in WA. The increasing trend in temperature is likely to be a result of a changing climate, and is likely to continue. The cause-effect pathway of temperature acting on seagrass currently represents a critical knowledge gap for the CSMC program which needs to be better elucidated to assist predictions for the future condition of seagrass, and to better inform the management of these communities.

Recommendation
A review of the literature around the effects of temperature on seagrasses is required to better define the cause-effect pathway for increasing temperature. This should be coupled with experimentation on local species to more accurately predict the consequences of temperature increases and thermal events.

The declines in seagrass density at the Warnbro Sound reference sites may be an issue for the ongoing protection of seagrass in Cockburn Sound. Lavery and McMahon (2011) concluded that under the EQS, declines at the reference sites did not pose a problem *per se*, as there were still default ‘absolute minima’ values written into the EQS (Environmental Protection Authority, 2005), against which impact sites could be assessed. Nevertheless, additional reference sites can help to identify potential pressures acting on a specific region and highlight the local nature of environmental changes. Moreover, if these sites were situated outside of the Perth metropolitan area a regional understanding of seagrass condition could be generated. An assessment could then be made as to whether the declines in seagrass reported here are confined to Cockburn and Warnbro Sounds or if they represent more general regional-scale losses.

Recommendation

Additional reference sites should be established outside of Cockburn and Warnbro sounds that are surveyed using the same protocols. These will provide a regional context for changes in the study area. However, a time-series of data will take a number of years to establish. To provide a more immediate contextualisation, a review of historical seagrass data from existing research and monitoring programs around the region and a meta-analysis of trends is required.

While many water quality parameters are monitored under the CSMC annual monitoring program, the way in which these data are collected do not provide data across a temporal scale appropriate for seagrass comparisons. While many parameters may reach their peak during the summer (e.g. temperature) others many not reach their highest level during this season. The temporal ‘smoothing’ of water quality values may not be the best approach when trying to link seagrass density to these pressures.

Recommendation

We recommend that, at least for temperature and light, *in situ* data loggers should be deployed at several sites across the study area. This would provide a more suitable, continuous dataset against which changes in seagrass density could be assessed. These could easily be deployed at a number of sites of interest and be swapped during routine maintenance of the seagrass monitoring sites.

The existing seagrass monitoring program utilises fixed, permanent quadrats which are surveyed annually. While the question of which is the better approach has been repeatedly raised (Centre for Marine Futures, 2009; Grochowski et al., 2011), and answered (Lavery and McMahon, 2011), these questions have typically surrounded issues of statistical power and cost. Here, we suggested that the reported losses of seagrass may be an artefact of the sampling procedure, through the repeated disturbance of measuring seagrass in fixed patches. This question has not yet been addressed and remains an important unknown in the monitoring program.

> **Recommendation**
> The CSMC implement an experimental study to determine the impact of repeated measurements on seagrass condition.

Quantitative data for some pressures (e.g. boating) were not available and proxies or older, qualitative information were used to characterise sites. Additional data is required for some of these pressures to complete the proper characterisation of sites. For example, a site-scale assessment of boating pressure, siltation and grazing rates would be very useful in further characterising long term monitoring sites. In addition, a detailed assessment of the wave climate in both Cockburn and Warnbro sounds, coupled with historical mapping of these areas would help to identify the causes and the history of blow-outs at some sites (e.g. the shallow reference sites and Woodman Point; Mohring and Rule, 2013).

> **Recommendation**
> The CSMC investigate pathways to collect additional data to fill knowledge gaps of the pressures acting on seagrass in Cockburn Sound.

There have been some discrepancies in the depth measurements at some sites. We used a GIS approach against a standard datum to calculate the depth of each site, and made comparisons based on the results of this analysis.

> **Recommendation**
> Future annual assessments should utilise the information reported here as a guide to determine which reference depths the impact sites correspond to. Further, we echo the recommendations of Lavery and McMahon (2011) who suggested formalising criteria in the Standard Operating Procedure to assist selecting appropriate reference sites against which to assess seagrass density in Cockburn Sound.

Finally, while the current monitoring program provides information about changes at a highly localised scale, it cannot provide information about changes at larger scales (e.g. meadow scale). Surveys of seagrass cover from multiple sites nested within each of the monitoring locations could provide information about changes across spatial scales which are not currently assessed, and could better link the current program to the proposed, systematic broad-scale mapping of seagrasses in Cockburn Sound (Lavery and McMahon, 2011; Western Australian Auditor General, 2010). These surveys could be rapid and represent little additional cost to the program if remote technology (e.g. drop cameras, towed video) is employed.

Recommendation

The CSMC investigate remotely-operated survey methods (e.g. drop cameras) which could be used to rapidly survey much larger areas and make meadow-scale assessments.

References

Bancroft, K.P., 1992. Preliminary investigations of echinoid aggregations in the seagrass meadow at Garden Island, Western Australia.

Bastyan, G.R., 1986. Distribution of seagrasses in Princess Royal Harbour and Oyster Harbour, on the south coast of Western Australia. (Technical Series, 1). Western Australian Department of Conservation and Environment, Perth.

Borum, J., Pedersen, O., Greve, T.M., Frankovich, T.A., Zieman, J.C., Fourqurean, J.W., Madden, C.J., 2005. The potential role of plant oxygen and sulphide dynamics in die-off events of the tropical seagrass, Thalassia testudinum. Journal of Ecology 93, 148–158.

Bourke, D., Chase, S., 2009. Study of the Contaminants in the Waters of Cockburn Sound 2008. Report to Cockburn Sound Management Council by PB.

Burt, J.S., Kendrick, G.A., Masini, R.J., Simpson, C.J., 1995. Light and Posidonia sinuosa meadows in the temperate coastal waters of Western Australia: II. Effect of epiphyte species assemblage and biomass on attenuating light to the leaf surface (Department of Environmental Protection technical series 62). Perth.

Byron, D., Heck, K., 2006. Hurricane effects on seagrasses along Alabama’s Gulf Coast. Estuaries and Coasts 29, 939–942.

Cambridge, M.L., Chiffings, A.W., Brittan, C., Moore, L., McComb, A.J., 1986. The loss of seagrass in Cockburn Sound, Western Australia. II. Possible causes of seagrass decline. Aquatic Botany 24, 269–285.

Cambridge, M.L., McComb, A.J., 1984. The loss of seagrasses in Cockburn Sound, Western Australia. I. The time course and magnitude of seagrass decline in relation to industrial development. Aquatic Botany 20, 229–243.

Carruthers, T.J.B., Dennison, W.C., Kendrick, G.A., Waycott, M., Walker, D.I., Cambridge, M.L., 2007. Seagrasses of south-west Australia: A conceptual synthesis of the world’s most diverse and extensive seagrass meadows. Journal of Experimental Marine Biology and Ecology 350, 21–45.

Cary, J.L., Masini, R.J., Simpson, C.J., 1995. The water quality of the southern metropolitan coastal waters of Perth, Western Australia: The influence of regional and local scale forcings. Environmental Protection Authority, Perth, Western Australia, Technical Series 64, Perth.

Centre for Marine Futures, 2009. A survey of selected seagrass meadows in Cockburn Sound, Owen Anchorage and Warnbro Sound: data report 2009 (Report to the Cockburn Sound Management Council). University of Western Australia.

Cockburn Sound Management Council, 2005. Environmental Management Plan for Cockburn Sound and its Catchment. Perth, Western Australia.

Cockburn Sound Management Council, 2009. State of Cockburn Sound; 2009 report. Cockburn Sound Management Council, Perth.

Cockburn Sound Management Council, 2010. Cockburn Sound Environmental Quality Monitoring Program 2009/2010. Perth, Western Australia.

Den Hartog, C., 1987. “Wasting disease” and other dynamic phenomena in Zostera beds. Aquatic Botany 27, 3–14.

Department of Environmental Protection, 1996. Southern Metropolitan Coastal Waters Study (1991-1994): Final Report. Department of Environmental Protection, Perth, Western Australia.

Department of Transport, 2013. Rockingham, Mangles Bay - Mooring Control Area [WWW Document]. URL http://www.transport.wa.gov.au/imarine/24459.asp (accessed 6.7.13).

Department of Water, 2006. Toxicants in Sediment Survey Report 2006, Cockburn Sound and Owen Anchorage. Report to the Cockburn Sound Management Council, Perth.

Diaz-Almela, E., Marbà, N., Duarte, C.M., 2007. Consequences of Mediterranean warming events in seagrass (Posidonia oceanica) flowering records. Global Change Biology 13, 224–235.

Duarte, C.M., 1991. Seagrass depth limits. Aquatic Botany 40, 363–377.

Duarte, C.M., 2002. The future of seagrass meadows. Environmental conservation 29, 192–206.

Duarte, C.M., Cebrian, J., 1996. The Fate of Marine Autotrophic Production. Limnology and Oceanography 41, 1758–1766.

Environmental Protection Authority, 2004. Revised manual of standard operating procedures for environmental monitoring against the Cockburn Sound Environmental Quality Criteria (No. Report 21).

Environmental Protection Authority, 2005. Environmental quality criteria reference document for Cockburn Sound (No. Report 21). Perth, Western Australia.

Fugro LADS Corp, 2009. Report of Survey, Western Australia, Two Rocks to Cape Natualiste, Bathymetry and Seabed Survey, LiDAR – April/May 2009. Adelaide, Australia.

Gerrodette, T., 1993a. Program TRENDS: User’s Guide. Southwest Fisheries Science Center, La Jolla, California.

Gerrodette, T., 1993b. TRENDS: Software for a power analysis of linear regression. Wildlife Society Bulletin 21, 515–516.

Grochowski, Waddington, K.I., Meeuwig, J., 2011. A survey of selected seagrass meadows in Cockburn Sound, Owen Anchorage and Warnboro Sound: data report 2011 (Report to the Cockburn Sound Management Council). University of Western Australia.

Heck, K.L., Hays, G., Orth, R.J., 2003. Critical evaluation of the nursery role hypothesis for seagrass meadows. Marine Ecology Progress Series 253, 123–136.

Hemminga, M.A., Duarte, C.M., 2000. Seagrass ecology. Cambridge University Press, New York.

Hoegh-Guldberg, O., Bruno, J.F., 2010. The impact of climate change on the world’s marine ecosystems. Science 328, 1523–1528.

Holley, D.K., Lawler, I.R., Gales, N.J., 2006. Summer survey of dugong distribution and abundance in Shark Bay reveals additional key habitat area. Wildlife Research 33, 243–250.

Holmer, M., Kendrick, G.A., 2013. High Sulfide Intrusion in Five Temperate Seagrasses Growing Under Contrasting Sediment Conditions. Estuaries and Coasts 36, 116–126.

Johannes, R.E., Pearce, A.F., Wiebe, W.J., Crossland, C.J., Rimmer, D.W., Smith, D.F., Manning, C., 1994. Nutrient characteristics of well-mixed coastal waters off Perth, Western Australia. Estuarine, Coastal and Shelf Science 39, 273–285.

Kendrick, G.A., Aylward, M.J., Hegge, B.J., Cambridge, M.L., Hillman, K., Wyllie, A., Lord, D.A., 2002. Changes in seagrass coverage in Cockburn Sound, Western Australia between 1967 and 1999. Aquatic Botany 73, 75–87.

Kirkman, H., 1997. Seagrasses of Australia. Prepared for the Department of the Environment, Canberra.

Kirkman, H., 1999. Pilot Experiments on Planting Seedlings and Small Seagrass Propagules in Western Australia. Marine Pollution Bulletin 37, 460–467.

Kirkman, H., Kirkman, J., 2000. Long-term seagrass meadow monitoring near Perth, Western Australia. Aquatic Botany 67, 319–332.

Kirkman, H., Kuo, J., 1990. Pattern and process in southern Western Australian seagrasses. Aquatic Botany 37, 367–382.

Langdon, M.W., Paling, E.I., van Keulen, M., 2011. The Development of Urchin Barrens in Seagrass Meadows at Luscombe Bay, Western Australia from 1985 to 2004. Pacific Conservation Biology 17, 48.

Lavery, P.S., 1994. Seagrass health in the Success Bank to Warnbro Sound Region., Department of Environmental Protection. Department of Environmental Management, Edith Cowan University, Perth.

Lavery, P.S., Gartner, A., 2008. A survey of selected seagrass meadows in Cockburn Sound, Owen Anchorage and Warnbro Sound: Health and Status 2008 – (No. Report Number No. 2008-10), Report to the Cockburn Sound Management Council (Department of Environment and Conservation). Coastal Marine Ecosystems Research, Edith Cowan University.

Lavery, P.S., How, J., 2006. Establishing reference and monitoring sites to assess a key indicator of ecosystem health (seagrass health) on the central west coast of Western Australia. Centre for Ecosystem Management, Edith Cowan University, Perth, Western Australia.

Lavery, P.S., McMahon, K., 2007. A survey of selected seagrass meadows in Cockburn Sound, Owen Anchorage and Warnboro Sound: health and status 2007 (Report to the Cockburn Sound Management Council). Edith Cowan University.

Lavery, P.S., McMahon, K., 2011. Review of Cockburn Sound SEP Seagrass Monitoring Program (No. CMER 2011-04), Report to the Cockburn Sound Management Council. Edith Cowan University, Perth.

Lee, K.-S., Park, S.R., Kim, Y.K., 2007. Effects of irradiance, temperature, and nutrients on growth dynamics of seagrasses: A review. Journal of Experimental Marine Biology and Ecology 350, 144–175.

Lemm, A.J., Masselink, G., Hegge, B.J., 1999. Offshore wave climate, Perth (Western Australia), 1994–96. Marine and Freshwater Research 50, 95–102.

Leoni, V., Vela, A., Pasqualini, V., Pergent-Martini, C., Pergent, G., 2008. Effects of experimental reduction of light and nutrient enrichments (N and P) on seagrasses: a review. Aquatic Conservation: Marine and Freshwater Ecosystems 18, 202–220.

Marbà, N., Duarte, C.M., 2010. Mediterranean warming triggers seagrass (Posidonia oceanica) shoot mortality. Global Change Biology 16, 2366–2375.

Masini, R.J., Cary, J.L., Simpson, C.J., McComb, A.J., 1995. Effects of light and temperature on the photosynthesis of temperate meadow-forming seagrasses in Western Australia. Aquatic Botany 49, 239–254.

Masini, R.J., Manning, C.R., 1997. The photosynthetic responses to irradiance and temperature of four meadow-forming seagrasses. Aquatic Botany 58, 21–36.

McMahon, K., Lavery, P.S., Mulligan, M., 2011. Recovery from the impact of light reduction on the seagrass Amphibolis griffithii, insights for dredging management. Marine Pollution Bulletin 62, 270–283.

Mohring, M.B., Rule, M.J., 2013. A Survey of Selected Seagrass Meadows in Cockburn Sound, Owen Anchorage and Warnbro Sound: data report (Prepared for the Cockburn Sound Management Council). Department of Environment and Conservation, Perth.

Occhipinti-Ambrogi, A., 2007. Global change and marine communities: Alien species and climate change. Marine Pollution Bulletin 55, 342–352.

OECD, 1993. OECD core set of indicators for environmental performance reviews. OECD Environment Monographs 83, 39.

Poloczanska, E.S., Babcock, R.C., Butler, A., Hobday, A.J., Hoegh-Guldberg, O., Kunz, T.J., Matear, R., Milton, D.A., Okey, T.A., Richardson, A.J., 2007. Climate change and Australian marine life. Oceanography and Marine Biology: An Annual Review 45, 407–478.

Preen, A.R., Lee Long, W.J., Coles, R.G., 1995. Flood and cyclone related loss, and partial recovery, of more than 1000 km2 of seagrass in Hervey Bay, Queensland, Australia. Aquatic Botany 52, 3–17.

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ralph, P., Runcie, J., Macinnis-Ng, C., 2010. Research into effects of oil and dispersed oil on temperate seagrases (Report to Australian Maritime Safety Authority). Institute for Water and Environmental Resource Management, and Department of Environmental Sciences University of Technology, Sydney.

Ralph, P.J., Durako, M.J., Enríquez, S., Collier, C.J., Doblin, M.A., 2007. Impact of light limitation on seagrasses. Journal of Experimental Marine Biology and Ecology 350, 176–193.

Ralph, P.J., Short, F.T., 2002. Impact of the wasting disease pathogen, Labyrinthula zosterae, on the photobiology of eelgrass Zostera marina. Mar Ecol Prog Ser 226, 265–271.

Renton, M., Airey, M., Cambridge, M.L., Kendrick, G.A., 2011. Modelling seagrass growth and development to evaluate transplanting strategies for restoration. Annals of Botany 108, 1213–1223.

Rose, T.H., Smale, D.A., Botting, G., 2012. The 2011 marine heat wave in Cockburn Sound, southwest Australia. Ocean Science 8, 545–550.

Rule, M.J., Bancroft, K.P., Kendrick, A.J., 2012. Baseline water quality of the Jurien Bay Marine Park: a benchmark for warm temperate Western Australia? Conservation Science Western Australia 8, 225–233.

Seddon, S., Cheshire, A.C., 2001. Photosynthetic response of Amphibolis antarctica and Posidonia australis to temperature and desiccation using chlorophyll fluorescence. Mar Ecol Prog Ser 220, 119–130.

Seddon, S., Connolly, R.., Edyvane, K.., 2000. Large-scale seagrass dieback in northern Spencer Gulf, South Australia. Aquatic Botany 66, 297–310.

Short, F.T., Ibelings, B.W., Den Hartog, C., 1988. Comparison of a current eelgrass disease to the wasting disease in the 1930s. Aquatic Botany 30, 295–304.

Short, F.T., Wyllie-Echeverria, S., 1996. Natural and human-induced disturbance of seagrasses. Environmental Conservation 23, 17–27.

Simpson CJ, Friedman K (Unpublished) The “What”, “How” and “Why” of monitoring: A practical guide for selecting biodiversity indicators and methods for a marine monitoring program. Unpublished manuscript

Sokal, R.R., Rohlf, F.J., 2001. Biometry. Freeman and Co., New York.

Statton, J., Dixon, K.W., Hovey, R.K., Kendrick, G.A., 2012. A comparative assessment of approaches and outcomes for seagrass revegetation in Shark Bay and Florida Bay. Mar. Freshwater Res. 63, 984–993.

Thomsen, M.S., Wernberg, T., Engelen, A.H., Tuya, F., Vanderklift, M.A., Holmer, M., McGlathery, K.J., Arenas, F., Kotta, J., Silliman, B.R., 2012. A Meta-Analysis of Seaweed Impacts on Seagrasses: Generalities and Knowledge Gaps. PLoS ONE 7, e28595.

Valentine, J.F., Heck Jr, K.L., 1999. Seagrass herbivory: evidence for the continued grazing of marine grasses. Marine Ecology Progress Series 176, 291–302.

Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., Foreman, K., 1997. Macroalgal Blooms in Shallow Estuaries: Controls and Ecophysiological and Ecosystem Consequences. Limnology and Oceanography 42, 1105–1118.

Walker, D.I., Lukatelich, R.J., Bastyan, G., McComb, A.J., 1989. Effect of boat moorings on seagrass beds near Perth, Western Australia. Aquatic Botany 36, 69–77.

Walker, D.I., McComb, A.J., 1990. Salinity response of the seagrass Amphibolis antarctica (Labill.) Sonder et Aschers.: an experimental validation of field results. Aquatic Botany 36, 359–366.

Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences 106, 12377 –12381.

Wernberg, T., Campbell, A., Coleman, M.A., Connell, S.D., Kendrick, G.A., Moore, P.J., Russell, B.D., Smale, D.A., Steinberg, P.D., 2012. Macroalgae and Temperate Rocky Reefs, in: Poloczanska, E.S., Hobday, A.J., Richardson, A.J. (Eds.), A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009, NCCARF Publication 05/09.

Western Australian Auditor General, 2010. Environmental management of Cockburn Sound Report 8 - September 2010. Perth, Western Australia.

Westphalen, G., O'Loughlin, P., Collings, G., Tanner, J., Eglington, Y., Bryars, S., 2005. Responses to reduced salinities of the meadow forming seagrasses Amphibolis and Posidonia from the Adelaide metropolitan coast (No. ACWS Technical Report No. 9, prepared for the Adelaide Coastal Waters Study Steering Committee). South Australian Research and Development Institute (Aquatic Sciences) Publication No. RD01/020814, Adelaide.

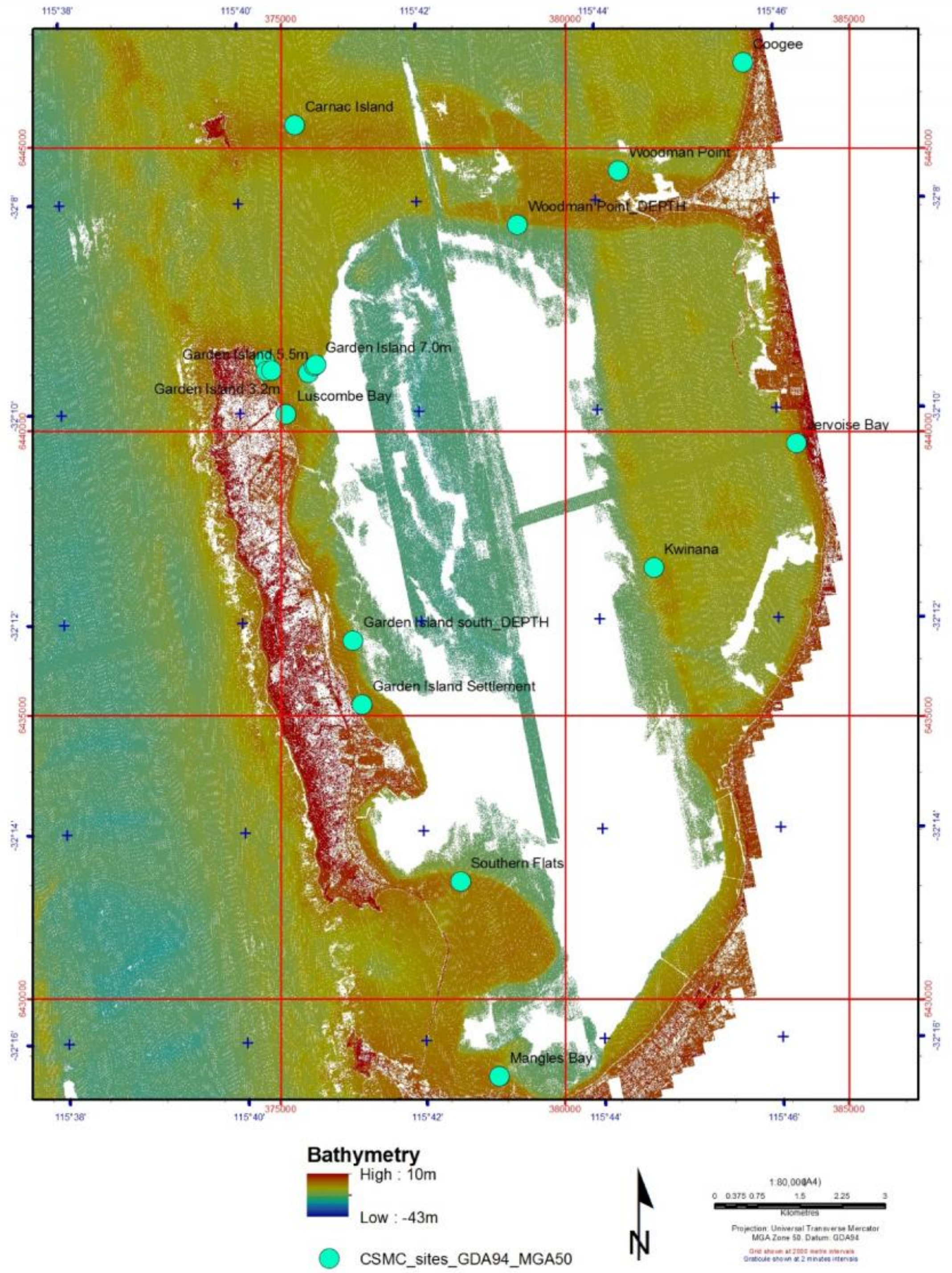
Wienczugow, K., Wilson, C., Paling, E.I., 2009. Water Quality of Cockburn and Warnbro Sounds (December 2008 to March 2009) (Report to the Cockburn Sound Management Council, Kwinana Industries Council and The Royal Australian Navy). Institute for Environmental Science (Report No. MAFRA 09/3) Murdoch University, Perth.

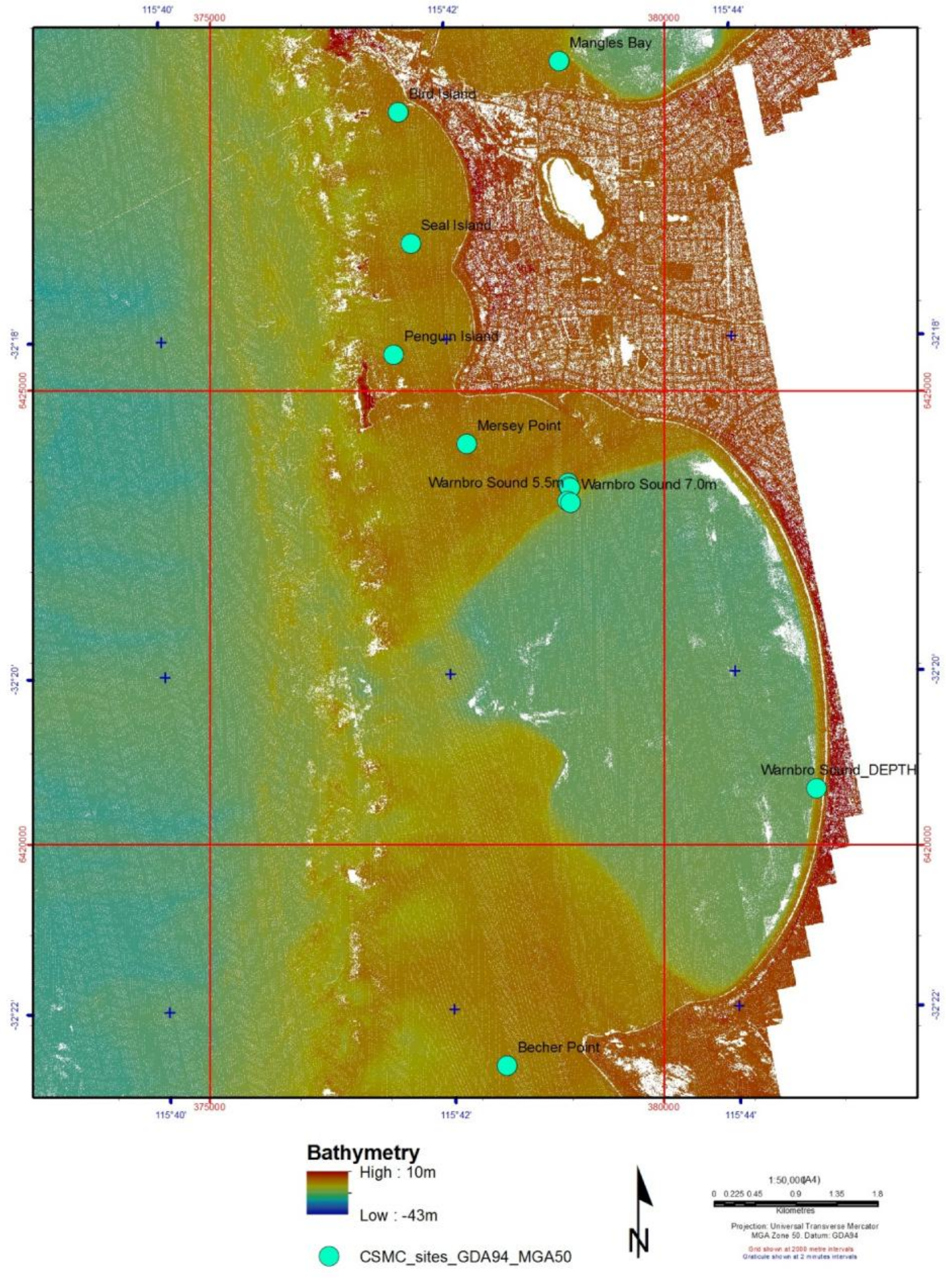
Williams, S.L., 2007. Introduced species in seagrass ecosystems: Status and concerns. Journal of Experimental Marine Biology and Ecology 350, 89–110.

Wood, S.N., 2010. Package "mgcv". GAMs with GCV/AIC/REML smoothness estimation and GAMMs by PQL.

Wood, S.N., Augustin, N.H., 2002. GAMs with integrated model selection using penalized regression splines and applications to environmental modelling. Ecological Monitoring 157, 157–177.

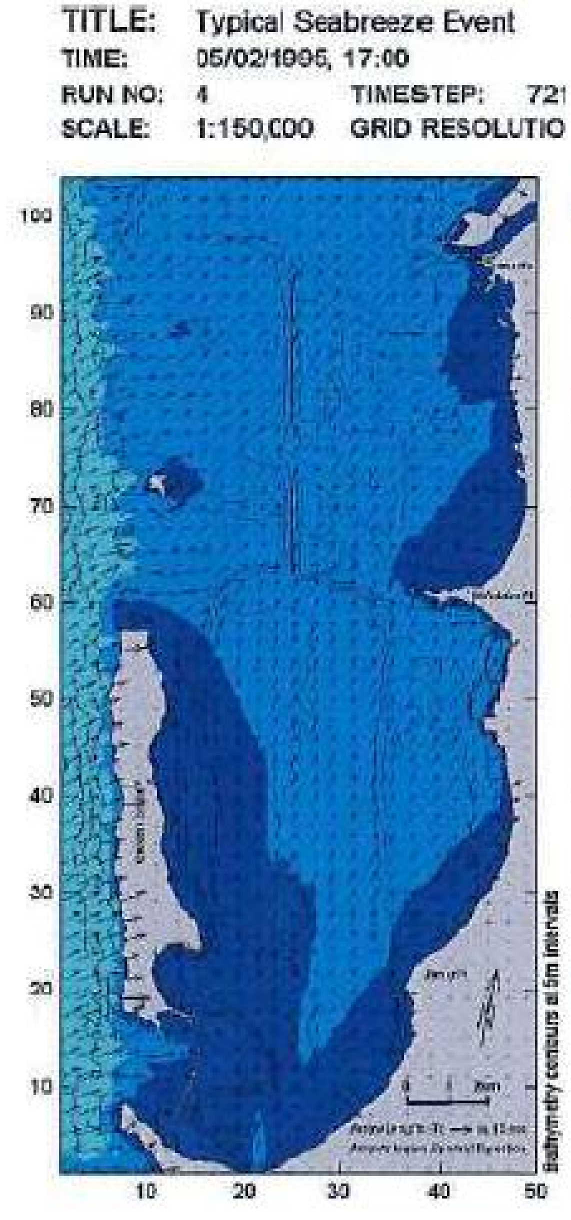
Appendix 1 LiDAR bathymetry GIS layer used to calculate the depth of each site in Cockburn and Warnbro sounds

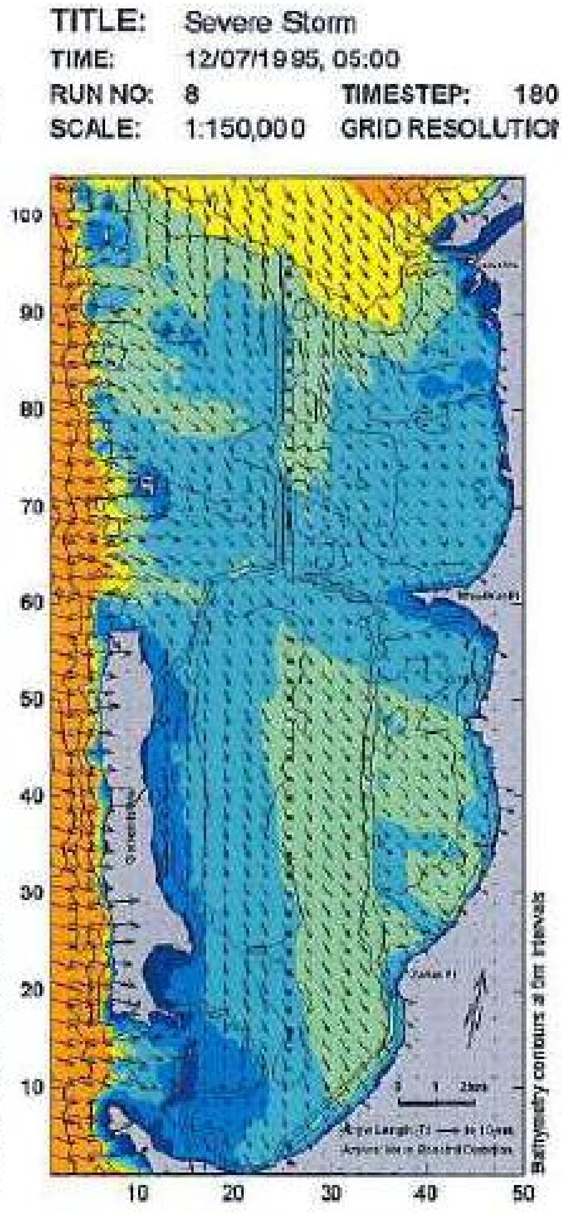




115°40'
375000
115°42'
380000
115°44'
Mangles Bay
Bird Island
Seal Island
Penguin Island
Mersey Point
Warnbro Sound 5.5m
Warnbro Sound 7.0m
Warnbro Sound_DEPTH
Becher Point
-32°18'
-32°20'
-32°22'
6425000
6420000
Bathymetry
High : 10m
Low : -43m
CSMC_sites_GDA94_MGA50
N
1:50,000(A4)
0 0.225 0.45 0.9 1.35 1.8
Kilometres
Projection: Universal Transverse Mercator
MGA Zone 50. Datum: GDA94
Grid shown at 2000 metre intervals
Graticule shown at 2 minutes intervals

Appendix 2 Modelled wave height and direction data





Appendix 3 A summary of pressures at each site

We used the trend analyses and ANOVA results as well as qualitative data and literature reviews to construct a pressure matrix for each of the seagrass sites in Cockburn and Warnbro sounds. A site was considered to be under pressure from a specific water quality parameter when: 1) ANOVAs showed a significantly worse condition than that found at reference sites; 2) where there was a trend of worsening water quality; or 3) values at a site were above the 80^{th} percentile (below the 20^{th} percentile for DO) reference values for more than 30% of years.

Carnac Island (OA9)

Carnac Island is probably the site under the least amount of pressure. The light environment, while poorer than the reference site, appears to have improved over the past 11 years. Besides temperature, Chl- a is the only parameter which still appears to be placing pressure on the seagrass at this site.

Coogee (OA10)

There were very limited light data for Coogee; however, these indicated that LAC values were above reference conditions, and we have, therefore, considered light to be a pressure at this site. Additional data is required to establish trends in light at Coogee. Chlorophyll *a* levels higher at this site and remain a pressure, as they may be contributing to the poorer light availability here.

Garden Island Settlement (G2)

Garden Island had a poorer light environment than the Warnbro Sound; however, it has improved over the past 11 years. While this site had significantly lower levels of Chl-*a* than the reference site, there was an increasing trend for this parameter. In addition, DO appears to be declining at this site.

Kwinana (CB)

Light attenuation values were significantly higher at Kwinana than at Warnbro Sound, and these do not appear to be improving. This may be a result of the increasing trend in Chl-*a* concentrations. Water movement at this site during periods of storms is likely to be higher here than at any other site. In addition, DO has declined in the past 11 years, and thus, the pressure from this parameter is increasing.

Luscombe (G3)

Luscombe Bay is one of only three sites where TP is still possibly an issue for seagrass, with pulses of TP and Chl-*a* above reference conditions being detected occasionally. While the concentration of TP is declining, there has been a siugnificant increase in the concentration of Chl-*a.* In addition, DO has worsened at this site.

Mangles Bay (CS11/MB)

Mangles Bay is the site under the highest level of pressure in Cockburn Sound. Light attenuation is higher here than in Warnbro Sound, and has not improved in the past 11 years, and Chl-*a* concentrations are often above the 95th percentile reference values. This is also the only site where pulses of TN above reference conditions were detected. In addition, there is significant pressure on seagrass communities at this site from boat moorings, which can scour and remove large amounts of seagrass and fragment the habitat (Walker et al., 1989). This site has generally been shown to have poorer water quality than other sites in Cockburn Sound as a result of the construction of the causeway to Garden Island, which restricts water circulation and encourages siltation at this site (Cockburn Sound Management Council, 2010)

Southern Flats (SF)

The Southern Flats site is also under significant pressure. The concentrations of NO_x were occasionally above reference values, and do not appear to have improved. In contrast, the concentration of OP which also occasionally rose above reference values has improved. The concentration of Chl-*a* has increased while the concentration of DO has declined.

Woodman (OA1)

The light environment at Woodman Point appears to be poor and is often worse than Warnbro Sound, and this has not improved over time. This may be related to the higher Chl-*a* concentrations at this site.

Jervoise (CS7)

The light environment appears to be particularly poor at Jervoise Bay. Light attenuation and Chl-*a* are almost always higher than at the Warnbro Sound reference site and neither have not improved over time. In addition, TP is occasionally higher than reference values and the DO concentration has declined significantly over the past 11 years.

Warnbro Sound reference sites

Total Nitrogen emerged as being a potential pressure at Warnbro Sound as it was generally higher than at all of the impact sites; however, concentrations of parameter have declined significantly. The concentrations of Chl-*a* have increased, while the concentration of DO has declined at Warnbro Sound (

Table 21).

Appendix 4 Additional monitoring sites in SW Western Australia

One of the key questions raised in this report is whether the declining trends in seagrass density (Chapter 2) represent a broad-scale, regional decline in seagrass condition, or whether declines are limited to Cockburn and Warnbro sounds. In order to effectively answer this question, it is recommended that additional monitoring sites, situated outside of the Perth metropolitan area, are established. Here we present a summary of the permanent seagrass monitoring sites outside of Cockburn Sound that are part of the Department of Parks and Wildlife's (DPaW, previously the Department of Environment and Conservation) monitoring, evaluation and reporting network. While many sites have only been recently established (Table 25), there are several which have a reasonable time-series of data. It will be possible to compile data from these sites for a more detailed, regional-scale analysis of the trends in seagrass condition, and with on-going collection of data there is the opportunity to assess trends in seagrass condition through time.

Table 25 Summary of regions and number of sites currently being monitored in SW Western Australia by the WAMMP.

Region	No. of suitable sites	Established	Sampling protocol	Years surveyed
Geographe Bay	TBD	TBD	Fixed	TBD
Shoalwater Islands Marine Park	6	2012	Partially fixed	2012, 2013
Marmion Marine Park	8	2011	Partially fixed	2011, 2012
Jurien Bay Marine Park	6	2003	Fixed	2003-2005, 2007, 2008, 2010-2013
Shark Bay Marine Park	11	2011	Partially fixed	2011

Probably the most significant set of sites which could be used as additional reference sites for the Cockburn Sound impact sites were established in 2003 in the Jurien Bay Marine Park to help define environmental Quality Criteria (EQC) for ecosystem health for the waters off the central west coast of WA (Lavery and How, 2006). Sites were established at three depths (2.5, 3.5 and 5.5m) at both Boullanger Island and Fisherman's Island, and therefore represent a suitable suite of reference sites to Cockburn Sound. These sites were established using the same protocols as the Cockburn Sound monitoring sites, and are therefore, directly comparable. Since 2010, these sites have been surveyed by the Western Australia Marine Monitoring Program (WAMMP) within the DPaW. Here we briefly examined the long term trends at these sites using the same analysis as for the Cockburn Sound data (Chapter 3). A decline in seagrass density was only found at Boullanger Island 5.5m (Figure 16; Table 26); however, this was at $\alpha = 0.2$. No significant trends ($\alpha = 0.05$) were detected at any of the Jurien Bay sites.

Table 26 Summary of the trend analysis conducted on data from the long term seagrass monitoring sites in Jurien Bay.

		Trend Analysis			
Site	Years of data	*P*	*F*	CV	Trend
Boullanger Island 2.5m	9	0.153	2.563	0.157	-0.208
Boullanger Island 3.5m	9	0.816	0.058	0.151	-0.037
Boullanger Island 5.5m	**9**	**0.071**	**4.516**	**0.135**	**-0.208**
Fishermans Island 2.5m	8	0.959	0.003	0.177	-0.010
Fishermans Island 3.5m	8	0.637	0.247	0.194	-0.099
Fishermans Island 5.5m	8	0.315	1.202	0.116	-0.120

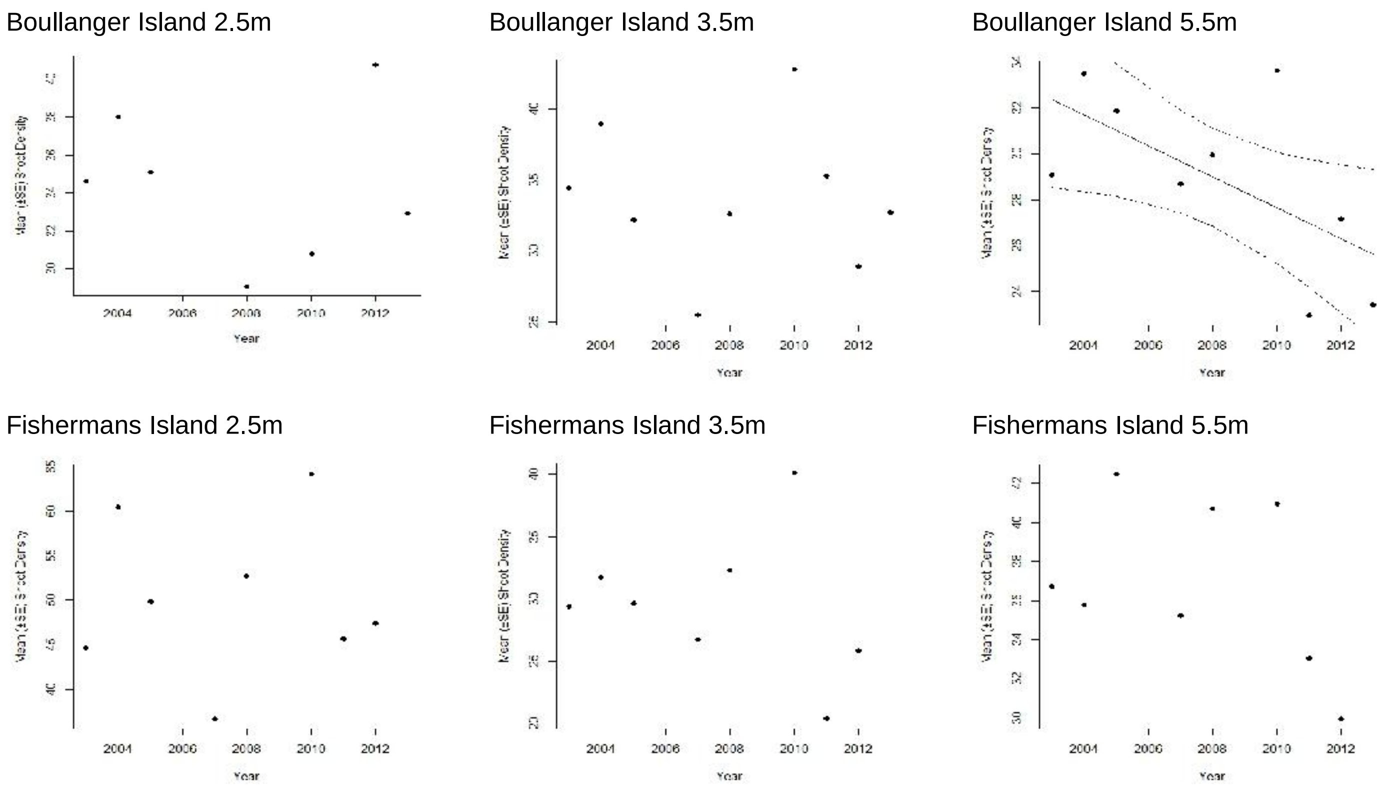


Figure 16 Mean seagrass densities at the seagrass sites in Jurien Bay from 2003-2013. Where significant (p = 0.2) trends existed the trend line (solid line) and the 95% confidence intervals (dotted line) are displayed.

The WAMMP, which has a state-wide focus on the condition of seagrass (and related pressures), has established numerous sites in existing temperate marine parks (Marmion, Shoalwater Islands and Shark Bay marine parks) and will be establishing long term sites in the new Ngari Capes Marine Park in the 2013-14 financial year[1]. While these sites are surveyed with a slightly different method (semi-permanent quadrats rather than the truly permanent quadrats used in Cockburn Sound), the sample size and level of replication are the same. These sites do not yet have a reasonable time-series of data to provide robust trend analysis, but they will provide valuable data in the next 3-5 years.

[1] Long term monitoring sites also exist in Geographe Bay (K. McMahon, pers com) which have been established using the same standard protocols as the Cockburn Sound site and some of these sites will be incorporated in future DPaW monitoring, evaluation and reporting.