Spatial and temporal analysis of water quality monitoring data collected from Cockburn Sound and Warnbro Sound between 1982/83 and 2013/14

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Report to the Cockburn Sound Management Council and the Western Australian Department of Water
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Summary, Conclusions and Recommendations

Water quality monitoring data from Cockburn Sound and Warnbro Sound for the period from 1982/83 to 2013/14 were analysed to determine spatial and temporal trends over time and to provide an up to date assessment of the status of water quality in Cockburn Sound and Warnbro Sound, the factors affecting it and its implications for ecosystem health.

Status of water quality parameters in relation to ANZECC thresholds and Cockburn Sound Environmental Quality Guidelines (EQGs) (2008-2014)

The 2008-2014 period represents the most recent period, thus reflecting the current situation. It has sufficient years to determine if trends exist, and it follows a period up until 2007 when significant improvements in a range of water quality indicators in Cockburn Sound were detected.

During this six year period, only 6 or 0.3 % of all Total Nitrogen measurements were above the ANZECC trigger value of 230 µgN/l and this parameter showed a decreasing trend between 2008 and 2014. However there were spatial differences. Consistent with what might be expected, the highest values were in Mangles Bay and in the largely enclosed Northern Harbour while the lowest were at the Garden Island and Warnbro Sound sites.

For Total Phosphorus, 7.1 % of samples were above the ANZECC trigger value of 20 µgP/l over the six years and the spatial patterns between sites were similar to that described above for Total Nitrogen.

There was a consistent excess of nitrogen in the water column relative to phosphorus with almost 80% of samples exceeding the Redfield ratio for nutrient uptake by phytoplankton.

Only 156 or 9.9% of light attenuation values were above the ANZECC guidance level (0.13 per meter) and local 2013/14 EQG for Moderate Protection Areas (MPA) of 0.11 per meter, however most of these occurrences were at the Northern Harbour site NH3 (65) and the James Point sites 9 and 9A (31). Only CS11 and CS13 in the southern High Protection Area (HPA) had mean values over the six year period which exceeded the local EQG for light attenuation of 0.09 per meter. Warnbro Sound (WS4) and the northern Cockburn Sound site (CS4) had the highest light penetration levels.

For chlorophyll $a$, 65% of all samples exceeded the ANZECC trigger value of 0.7 µg/l and 26% exceeded this by more than double the trigger value over the six years. Sites with mean chlorophyll $a$ levels more than double the ANZECC trigger value were the eastern shore and southern Cockburn Sound sites. In Northern Harbour, 97% of all samples exceeded the ANZECC trigger value by three times. However, only five sites had mean values over the six year period which exceeded the 2013/14 EQG values for Cockburn Sound. Three HPA sites, Mangles Bay (MB), CS11 and CS13, all in the southern HPA exceeded the local chlorophyll $a$ EQG of 0.9 µg/l. Two MPA sites, Northern Harbour (NH3) and Kwinana Bulk Jetty (CS9A) exceeded the local chlorophyll $a$ EQG of 1.5 µg/l.
Long term patterns and trends (1982-2014)

There was a significant long term increase in both surface and bottom water temperature in Cockburn Sound with increases in surface waters between 1985 and 2014 of 0.0325 ± 0.016 °C per year. These rates of change are very similar to those reported elsewhere off the Western Australian coastline and are attributed to global climate change.

Total Nitrogen and Dissolved Inorganic Nitrogen (DIN) levels showed marked decreases during two periods; in the early 1990s and around 2006-2007. The former can be attributed to reductions in nitrogen inputs from the old treated waste water outfall and from the CSBP site. The reason for the fall about a decade ago is not known but maybe related to the commissioning of the Sepia Depression Ocean Outlet Landline (SDOOL). CSBP Limited commenced discharging into the SDOOL in October 2005 the discharge of treated wastewater and the discharge from the Water Corporation’s wastewater treatment plants at Woodman Point and Point Peron also began around this time (Water Corporation 2012). Light attenuation levels also improved notably around 2006. Light attenuation levels at most sites have improved generally since 2000, but several MPA and HPA sites showed further coincident improvement to below current EQGs around 2006. Interestingly, notable improvements in chlorophyll $a$ occurred slightly earlier in 2005.

Phosphorus showed a marked decrease in around 1999 with means of all sites falling below the ANZECC trigger value and remaining so. Mean temperatures over the six years did not exceed the 2013/14 MPA or HPA EQGs at any site.

Short term patterns and trends (2008-2014)

Total Nitrogen showed a gradually decreasing trend between 2008 and 2014.

Improvements in dissolved inorganic nitrogen levels since about 2007 have meant that many nitrite/nitrate, ammonium and FRP samples are below detection limits of the methods used from 2007 onwards. These nutrients are those most easily taken up and utilised by plants and a change in methodology with lower detection limits is recommended for these parameter measurements to be instructive.

The spatial distribution of nutrients and chlorophyll $a$ show a gradient with the highest concentrations in the south-east part of Cockburn Sound. This pattern is consistent with a predicted concentration of submarine groundwater nutrient inputs in the region south of James Point but may also be related to poor circulation in this area relative to other parts of the Sound.

A significant shift (increase) in chlorophyll $a$ occurred in 2011 at WS4 in Warnbro Sound to above the ANZECC trigger value for the first time since 2003. This has been sustained for 4 years and may warrant investigation.

Despite some improvements in light attenuation since the early 2000s, light conditions at the seafloor remain close to the limit for seagrass growth in some areas of the Sound, most particularly the eastern edge in depths where seagrass occurred historically.
At sites away from the eastern shore such as in the north of Cockburn Sound and at Garden Island, there is also a hint of a very recent further improvement in light levels at some sites in 2013 and 2014 but it is too early to tell if this is significant or sustained.

The anomalous warming event in 2011 was clearly evident in the temperature data.

**Recommendations for ongoing monitoring**

The weekly summer (or more correctly non-river flow period) sampling undertaken is done for valid reasons to facilitate interannual comparison, as variable winter rains and flows can influence nutrient levels. However, it does not permit capturing some of the seasonal variation that might be instructive. Continuous monitoring of light and temperature using moorings could be considered as a cost effective way of obtaining data on some parameters year round.

A change in methodology for measuring phosphate, ammonium and nitrite/nitrate with lower detection limits is recommended.

Water quality measurements are undertaken at just two sites in Warnbro Sound and it may be prudent to consider increasing the number of reference sites there in line with the additional seagrass sites monitored. The increase in chlorophyll $a$ at the Warnbro Sound reference site since 2011 warrants investigation.

**Issues to do with data analysis**

Care needs to be taken in the analysis and interpretation of patterns in the data and we have attempted to explain these.

- Many parameters are correlated with each other.
- There was a significant seasonal trend in four parameters across the 15-16 week summer sampling period; temperature, dissolved oxygen, chlorophyll $a$ and light.
- Some parameters show step change (e.g. nitrogen in the 2006 - 2007 period) rather than gradual change and identifying these can be useful and important in interpretation of environmental health.
- There can be long term changes in parameters unrelated to local conditions (e.g. global sea temperature change).
- There can be anomalous events such as algal blooms or heat waves which cause spikes in some years (e.g. WA marine heatwave in 2011).

For these reasons simple regression-over-time approaches that have been used in some previous studies, which simply look for increasing and decreasing trends in annual means, especially over relative short periods of a decade or so, need to be viewed cautiously, so in general we have avoided these.

**Implications for managed aquifer recharge (MAR)**

Once of the possible consequences of MAR using secondary treated wastewater is that it may increase the flux of nutrients to Cockburn Sound from terrestrial (groundwater) sources through submarine groundwater discharge (SGD). The potential impact is two-fold, mobilisation of existing nutrients in groundwater due to increased SGD and inputs of nutrients from the
wastewater. The overall decreasing trend in nutrient concentrations over time may indicate that the inputs to Cockburn Sound, including from SGD, may be decreasing. As decreasing nutrient concentrations in the Sound as a whole are not resulting in improvements in chlorophyll \( a \) at some sites (especially in the southern area of the Sound), it is not clear how the likely increase in nutrient discharge due to MAR may impact the Sound other than seeing a levelling off or increase in N and P concentrations. However nutrient mitigation either through natural processes or engineered measures may limit the impacts. Additionally, depending on the location, abstraction of groundwater associated with MAR schemes could be designed to intercept the majority of the nutrient load before it enters the Sound. The impacts of MAR therefore contingent on a number of conditions. Depending on the site, volume of wastewater recharged, wastewater nutrient concentration and degree of interception, Donn et al. (2015) showed that the additional delivery of nutrient to the Sound as a result of MAR varied by two orders of magnitude (3 to 180 tN/yr). Any impacts could be expected to be localised given the patterns found in this study suggest that poor circulation in the southeast section of Cockburn Sound and/or submarine groundwater discharge (SGD) are contributing to sub-optimal water quality conditions in that area especially the highly correlated parameters of light and chlorophyll \( a \).

2 Background

CSIRO, through its partnership with Australian Water Recycling Centre of Excellence (AWRCOE), Kwinana Industry Council and the WA Department of Water are undertaking an investigation of managed aquifer recharge opportunities in the Cockburn Sound catchment (McFarlane 2015). To augment this work it was proposed to examine historical trends in trends in water column nitrogen in Cockburn Sound relative to existing loads, concentrations and fluxes.

This will enable the role of groundwater discharge to the Sound to be placed into a broader context, and the risks and need for mitigation practices to be assessed were the Superficial Aquifer to be recharged with secondary treated wastewater as an alternate water source to meet growing industry demand. This study will also meet the needs of other parties, especially the Cockburn Sound Management Council’s need to address an Auditor General request in 2010 to analyse historical trends in ecosystem health in Cockburn Sound, including trends in water quality (OAG, 2010).

One of the constraints identified in the AWRCOE study of the use of treated wastewater was the impacts of additional nutrient export, through submarine groundwater discharge (SGD), to the Cockburn Sound as a result of MAR (Donn et al. 2015). However to sufficiently address the impacts of MAR the changes to SGD and nutrient loads need to be assessed in context with other nutrient inputs and cycling processes that impact the Sound.

It has been known for some time that groundwater in the Kwinana region intersects with the marine waters of Cockburn Sound through natural submarine groundwater discharge. Groundwater fluxes delivery both natural and anthropogenic nutrients (including ammonium and nitrate) and total nitrogen loads from groundwater were estimated to be 234 ± 88 tonnes/year (Smith et al. 2003). This is regarded as significant and is consistent with estimates of 212 tonnes in 2000 (CSMC 2001). However it needs to be considered in context relative to historical total nitrogen inputs of total discharge (including SGD) into the Sound of over 2000 tonnes per annum in 1978, 1080 tonnes in
1990 and 300 tonnes in 2000 (CSMC 2001). Other fluxes into Cockburn Sound are also significant. For example, estimates of nutrient cycling in the marine sediments are up to 1950 tonnes/year (CSMC, 2001). In Cockburn Sound this problem is compounded by poor flushing of the coastal embayment (up to 44 days residence time in summer; CSMC 2001) resulting in its sediments having a high organic load which in turn continuously resupplies the water column with nutrients through biological activity and biogeochemical processes.

Due to historically poor water quality management and the consequent loss of more than 90% of the seagrass in Cockburn Sound, measures have been implemented since the late 1980s to reduce nutrient inputs to Cockburn Sound from terrestrial point sources. These have been largely successful although the legacy of historical anthropogenic nitrogen loads in groundwater and marine sediments and poor flushing of parts of Cockburn Sound continue to impact water quality and it is timely that an up to date assessment of the nitrogen trends in Cockburn Sound be made.

This synthesis of historical data from the CSMC water quality monitoring program, forms the first component of this study. Later components will include developing a nitrogen budget for Cockburn Sound and a survey to determine whether spatial variation in SGD into Cockburn Sound can be detected.

3 Historical context

Water quality and environmental health and public amenity of Cockburn Sound are intrinsically linked and the sentinel of this has largely been the seagrass meadows. Between 1967 and 2002, 843 hectares or more than 90% of the seagrass meadows were lost (DAL 2004) with the primary cause being attributed to nitrogen inputs from CSBP fertiliser, the Kwinana Nitrogen Company (KNC) and the Woodman Point Wastewater Treatment Plant (WPWTP) causing the proliferation of epiphytic and unattached benthic algae resulting in the shading and death of the seagrass (Cambridge and McComb 1984; Cambridge et al., 1986; Kendrick et al. 2002). During the period from 1977-1979 it is estimated that the daily N and P inputs in direct discharge to Cockburn Sound were 4.986 tN per day (1820 tN/yr) and 3.776 tP per day (1378 tP/yr) (DCE 1979). Of these inputs, 87% of P and 62% of all N came from CSBP and the KNC and 28% of N came from the WPWTP. Since that time reducing nutrient loading to the Sound and maintaining the health of the remaining seagrass beds have been key foci for government and industry. Removing direct inputs from fertiliser manufacture and upgrade of sewage treatment and outfall facilities have provided the most gains in gradually reducing the total nutrient inputs (including SGD) into Cockburn Sound to about 2000 tN per annum in 1978, 1080 tN in 1990 and 300 tN in 2000 (CSMC 2001). However, legacy issues remain from agricultural and industrial contamination of groundwater (Trefry et al. 2006) and nitrogen from groundwater is now believed to be the main source of N loading. Previous estimates of this were 212 tN per annum (CSMC 2001) and 234 ± 88 tN per annum (Smith et al. 2003). Using more recent estimates of SGD (Donn et al. 2015) and N concentrations given by Smith et al. (2003), Donn et al. (2015) calculated groundwater nitrogen loads of between 450 and 920 tN per annum for the period 1995 to 2012. The differences between the estimates of Smith et al. (2003) and Donn et al. (2015) are related to differences in the modelled SGD, both of which have their uncertainties. Both estimates of N loading are regarded as significant and are consistent with or higher than estimates of 212 tN on 2000 (CSMC 2001).
Lastly, the very slow flushing of Cockburn Sound (up to 44 days residence time in summer; CSMC 2001) as a result of both the natural constraints of Garden Island creating a semi-enclosed embayment and the Garden Island Causeway1 (built in 1971-1973) has meant legacy nutrients remain tied up in sediments in the Sound and as such the most significant of all nutrient fluxes in Cockburn Sound is nutrient cycling from marine sediments which are estimated to be up to 1950 tonnes/year (CSMC 2001). As a result of improvements in water quality, seagrass loss was halted and for a significant period monitoring had shown no deterioration in many of the environmental indicators for Cockburn Sound (CSMC 2001; CSMC 2007). However, Smith et al. (2003) noted that despite continuous improvement in reducing nutrient pollution to Cockburn Sound, trends in water quality had not responded accordingly and chlorophyll $a$ levels remained above environmental quality guidelines at that time. More than a decade on there have been improvements in key water quality parameters including chlorophyll $a$ and light attenuation (CSMC 2014). However, over time, a number of water quality parameters have continued to exceed environmental quality guidelines at some sites in some years, especially in the southern part of Cockburn Sound (e.g. CSMC 2013). In 2013 the high protection zone of Cockburn Sound was separated into two areas (north and south) for reporting purposes. More recently, analysis of monitoring data has shown a decline in seagrass density in both Cockburn Sound and the reference site in Warnbro Sound (Mohring and Rule 2013) and this follows a recommendation from the Western Australian Auditor General that the suitability of Warnbro Sound as a reference site be investigated (OAG 2010). It is within this context that we have undertaken a comprehensive analysis of water quality data collected from Cockburn Sound since 1982/83.

4 Sources of data and other information

Water quality data was sourced through the Cockburn Sound Management Council (CSMC) and the Office of the Environmental Protection Authority. The data represents data collected for the CSMC by the Marine and Freshwater Research Laboratory based at Murdoch University. The water quality dataset was compiled from a number of different datasets containing data from November 1982 to March 2014. Samples were collected over the non-river flow or ‘summer’ period, from the beginning of December until the end of March, on a weekly basis. This period was selected as the most stable period, facilitating interannual comparison, as variable winter rains and flows can influence nutrient levels (EPA 2015). During the monitoring period 22 sites have been monitored with minor location changes for three sites (Table 4.1). Currently there are 20 sites monitored (Figure 4.1) located within different ecological protection areas in Cockburn Sound and the reference location in Warnbro Sound (Figure 4.2 and Table 4.1).

Early in the data record the sampling did not always occur on sequential years (1982/83, 1984/85, 1985/86, 1986/87, 1989/90, 1990/91, 1992/93) however from 1996/97 monitoring has occurred yearly. The parameters measured are shown in Table 4.2 with nutrients (nitrogen and phosphorus), chlorophyll $a$, salinity, temperature and dissolved oxygen measured throughout the monitoring period (occasionally some parameters at some sites in some years have not been recorded). Additional in-situ parameters were added to the parameter list as indicated in Table 4.2. For

1 It is worth noting here that the solid fill structure of the Garden Island causeway was not the Australian Navy’s choice of construction, but rather that of the Fremantle Port Authority who wanted protection for shipping from waves. The Navy’s preference was for a bridge structure (CSMC 2001).
nutrients and chlorophyll a, integrated samples were collected at the surface, mid-depth and bottom using Niskin Bottles and combined until 2006/07 summer, thereafter depth integrated samples were collected using a pumped hose passed vertically through the water column at a constant rate. The detection limits for the nutrient measurements are shown in Table 4.2 and one half of the detection limit was used in the statistical analysis. Light attenuation was determined from measurements of irradiance taken at 1 m and 7 m below the surface (Model LI-1400, Licor Inc., Nebraska, USA) and determined using the following equation;

\[
\text{Light attenuation} = \frac{\log_{10} l(1m) - \log_{10} l(7m)}{6}
\]

where \( l \) = irradiance at either 1 m or 7 m
<table>
<thead>
<tr>
<th>Site</th>
<th>Description</th>
<th>Protection Category</th>
<th>Approx Depth (m)</th>
<th>Commenced Monitoring</th>
<th>Ceased Monitoring</th>
<th>Zone</th>
<th>Easting</th>
<th>Northing</th>
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</thead>
<tbody>
<tr>
<td>CS4</td>
<td>Cockburn Sound northern end deep</td>
<td>High</td>
<td>20.9</td>
<td>1/01/1983</td>
<td></td>
<td>50H</td>
<td>376829</td>
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<td>CS5</td>
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<td>50H</td>
<td>379308</td>
<td>6441958</td>
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<td>CS7</td>
<td>Jervoise Channel south of Southern Harbour</td>
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<td>1/01/1983</td>
<td></td>
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<td>50H</td>
<td>382749</td>
<td>642651</td>
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<td>CS6A</td>
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<td>20/01/1998</td>
<td></td>
<td>50H</td>
<td>382749</td>
<td>642651</td>
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<td></td>
<td>50H</td>
<td>379337</td>
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<td>CS9</td>
<td>Kwinana Bulk Terminal (KBB2)</td>
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<td>1/01/1983</td>
<td></td>
<td>50H</td>
<td>383098</td>
<td>6435629</td>
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<td>CS10</td>
<td>Outside Northern Harbour</td>
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<td>19.2</td>
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<td>1/04/2003</td>
<td>50H</td>
<td>381396</td>
<td>6430437</td>
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<td>CS10N</td>
<td>Bulk Grain Terminal (CBH) (CS10N replaced CS10)</td>
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<td>1/12/2004</td>
<td></td>
<td>50H</td>
<td>381593</td>
<td>6430569</td>
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<td>CS11</td>
<td>Mangles Bay deep water basin</td>
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<td>18.0</td>
<td>1/01/1983</td>
<td></td>
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<td>378890</td>
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<td>1/01/1997</td>
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<td>50H</td>
<td>383291</td>
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<td>CS9A</td>
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<td>1/01/2001</td>
<td></td>
<td>50H</td>
<td>382367</td>
<td>6432936</td>
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<td>WS4</td>
<td>Warnbro Sound central basin</td>
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<td>50H</td>
<td>379741</td>
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<td>WSSB</td>
<td>Warnbro Sound Safety Bay shallow</td>
<td>Reference Site</td>
<td>2.4</td>
<td>1/01/2001</td>
<td></td>
<td>50H</td>
<td>378444</td>
<td>6424599</td>
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<td>SF</td>
<td>Southern Flats shallow</td>
<td>High</td>
<td>3.5</td>
<td>1/01/2001</td>
<td></td>
<td>50H</td>
<td>378716</td>
<td>6431322</td>
</tr>
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<td>CB</td>
<td>Challenger Beach bank</td>
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<td>9.3</td>
<td>1/12/2002</td>
<td></td>
<td>50H</td>
<td>381133</td>
<td>6438605</td>
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<tr>
<td></td>
<td>Moderate</td>
<td>15.0</td>
<td>1/12/2002</td>
<td>1/12/2004</td>
<td></td>
<td>50H</td>
<td>377319</td>
<td>6433380</td>
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<td>G1</td>
<td>Careening Bay HMAS Stirling</td>
<td>Moderate</td>
<td>15.2</td>
<td>1/12/2004</td>
<td></td>
<td>50H</td>
<td>377121</td>
<td>6433158</td>
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<td>G2</td>
<td>Garden Island central HMAS Stirling</td>
<td>High</td>
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<td>1/12/2002</td>
<td></td>
<td>50H</td>
<td>376039</td>
<td>6436793</td>
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<td>G3</td>
<td>Garden Island north HMAS Stirling</td>
<td>High</td>
<td>13.1</td>
<td>1/12/2002</td>
<td></td>
<td>50H</td>
<td>375728</td>
<td>6441317</td>
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<tr>
<td>CS12</td>
<td>Callista Channel WC Desalination Plant</td>
<td>Moderate</td>
<td>10.0</td>
<td>1/12/2006</td>
<td></td>
<td>50H</td>
<td>383677</td>
<td>6436972</td>
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<tr>
<td>CS13</td>
<td>Cockburn Sound southern deep water</td>
<td>High</td>
<td>20.4</td>
<td>1/12/2008</td>
<td></td>
<td>50H</td>
<td>380207</td>
<td>6431054</td>
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<td>MB</td>
<td>Mangles Bay shallow near shore</td>
<td>High</td>
<td>1.3</td>
<td>8/02/2010</td>
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<td>50H</td>
<td>378085</td>
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<td>NC</td>
<td>North Control</td>
<td>Reference Site</td>
<td>8.3</td>
<td>1/01/1983</td>
<td>1/12/2002</td>
<td>50H</td>
<td>372954</td>
<td>6443318</td>
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<td>SC</td>
<td>South Control</td>
<td>Reference Site</td>
<td>7.7</td>
<td>1/01/1998</td>
<td>1/12/2008</td>
<td>50H</td>
<td>376063</td>
<td>6430632</td>
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</table>
Figure 4.1 Map showing location of current and historical Cockburn Sound Management Council (CSMC) sampling locations in Cockburn and Warnbro Sounds and industries that potentially contribute to nutrient discharge either directly (in past) or via submarine groundwater discharge.
Figure 4.2 Location of the Cockburn Sound Management Council (CSMC) water quality monitoring locations with respect to the ecological protection levels outlined by the State Environmental (Cockburn Sound) Policy 2005 (updated in 2010). The green line separating the lower third of Cockburn Sound reflects the 2013 decision to split the high protection zone into a northern and southern area for the purpose of reporting.
Table 4.2 List of parameters measured as part of the Cockburn Sound Management Council water quality monitoring program

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Commenced</th>
<th>Sampling method</th>
<th>Detection limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$-N / NH$_4$-N</td>
<td>Ammonia / ammonium, as nitrogen</td>
<td>µg/L</td>
<td>1982/83</td>
<td>Integrated</td>
</tr>
<tr>
<td>NO$_x$-N</td>
<td>Nitrate + nitrite, as nitrogen</td>
<td>µg/L</td>
<td>1982/83</td>
<td>Integrated</td>
</tr>
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<td>1982/83</td>
<td>Integrated</td>
</tr>
<tr>
<td>FRP</td>
<td>Filterable reactive phosphorus</td>
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<td>1982/83</td>
<td>Integrated</td>
</tr>
<tr>
<td>TP</td>
<td>Total phosphorus</td>
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<td>1982/83</td>
<td>Integrated</td>
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<td>1982/83</td>
<td>Integrated</td>
</tr>
<tr>
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<td>2011/12</td>
<td>Integrated</td>
</tr>
<tr>
<td>Chlorophyll c</td>
<td> </td>
<td>µg/L</td>
<td>2011/12</td>
<td>Integrated</td>
</tr>
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</tr>
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<td>°C</td>
<td>1984/85</td>
<td>Surface, Bottom</td>
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<tr>
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<td>Integrated</td>
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<td></td>
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<td>Integrated</td>
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<td>2011/12</td>
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<td>2011/12</td>
<td>Surface, Bottom</td>
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<tr>
<td>Fluorescence</td>
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<td> </td>
<td>2011/12</td>
<td>Surface, Bottom, Integrated</td>
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</table>

5 Spatial patterns and trends

5.1 Contour maps

Contour maps have been drawn for several key parameters including total nitrogen, total phosphorus, chlorophyll a, and vertical light attenuation, to aid examination of recent mean spatial trends in the Sound (2008-2014). Detection limits for DIN (NO$_x$; 2µgN/l; NH$_3$; 3µgN/l) and FRP (2µgP/l) were in general too high to use these parameters in either the spatial or temporal analyses for the most recent period of sampling (2008-2014). This period was chosen as it represents the current situation which is of most interest, but with sufficient years to determine trends that might exist, and it follows a period up until 2007 when significant improvements in a range of water quality measures in Cockburn Sound were detected (see Section 6.3). The maps were constructed by interpolating the mean depth-averaged field measurements (2008-2014) at each monitoring site onto a regular grid, and assuming a linear trend between adjacent points. Due to unusually high nutrient concentrations within Northern Harbour (NH3) and Mangles bay (MB), it was decided to omit them from the mapping procedure as they distort the contours, extending the influence of those sites to an unrealistic extent. The measured values for NH3 and MB are included in the caption of each figure for reference.

Total nutrient concentration (total N and total P) generally increases toward the mainland coast, and the south, with the highest concentrations occurring in the vicinity of stations CS9, CS9A and CS10
(Figure 5.1 and Figure 5.2). Meanwhile, the lowest concentrations occur along the northern perimeter of the Sound at stations G3, CS4 and CS5. Similar spatial patterns were reported as part of the Southern Metropolitan Coastal Waters Study (Simpson et al. 1996), based on measurements of dissolved nitrate made during 1991 when the dissolved nutrient levels in the Sound were higher.

The relatively high concentration of total nitrogen and phosphorus observed south of James Point is consistent with estimates of submarine groundwater nutrient inputs in this region (Figure 5.3) derived from recent groundwater modelling (Donn et al. 2015). However, the highest mean levels of total nitrogen occur in the vicinity of CS10/CS10N, where beach pore water sampling has not previously found high levels of nitrogen or phosphorus (Smith et al. 2003).

![Figure 5.1 Spatial variation in mean total nitrogen concentration (µg l⁻¹) in Cockburn Sound (2008-2014). Station locations are shown by filled circles. Values for Northern Harbour (NH3, 173 µg l⁻¹) and Mangles Bay (MB, 171 µg l⁻¹) are not included.](image)
Figure 5.2 Spatial variation in mean total phosphorus concentration (µg l⁻¹) in Cockburn Sound (2008-2014). Station locations are shown by filled circles. Values for Northern Harbour (NH3, 18 µg l⁻¹) and Mangles Bay (MB, 19 µg l⁻¹) are not included.

Figure 5.3 Example of spatial distribution of total nitrogen (TN) load based on estimated submarine groundwater discharge (Donn et al., 2015) and beach pore water concentrations (Smith et al. 2003).
The spatial trends in chlorophyll a pigment (used as a proxy for phytoplankton biomass) are consistent with the distribution of nutrients, with highest concentrations in the south east of the Sound (Figure 5.4). There is also some evidence for a local high in the vicinity of station G1. Both these areas of high chlorophyll a have moderate ecological protection status (Figure 4.2).

The final two contour maps in this section consider the mean underwater light conditions in the Sound. The analysis shows that the vertical attenuation rate broadly follows the nutrient and chlorophyll a pattern showing a moderate increase toward the coast and the south (Figure 5.5). The highest mean attenuation rates (excluding Northern Harbour, NH3) are recorded for station CS9A (0.108 m\(^{-1}\)).

The vertical light attenuation rate (\(kd\)) has been combined with bathymetry data (\(h\)) to estimate the fraction of light reaching the seabed (\(f\)), calculated as:

\[
f = 10^{-kd.h}
\]

This approach assumes that light attenuation is constant with depth, and ignores more rapid attenuation of light in the upper layers. This may lead to an overestimation of the fraction of light reaching the seabed. Application of a more accurate model would require more detailed measurements of the vertical profile of light.

The analysis (see Fig. 5.6) suggests that except for the shallow nearshore areas, the seabed light conditions in most parts of Cockburn Sound are at, or below, the minimum light requirement for seagrass growth of 11% (Duarte 1991), with requirements expected to be even higher in the case of
elevated temperature (Masini et al. 1995), and epiphyte growth (Ralph et al. 2007). Lowest seabed light intensities are expected in the central southern basin where reduced water clarity and deep water combine to limit the amount of light reaching the seabed to <2% (Figure 5.6). Highest seabed light intensities are expected along the eastern Garden Island coastline. The extensive shelf on the eastern part of Cockburn Sound where much of the historic seagrass loss has occurred (Kendrick et al. 2002) is expected to only receive about 20% of surface light and may represent marginal conditions for seagrass growth and could have implications for recovery of lost seagrass.

Figure 5.5. Spatial variation in mean vertical light attenuation rate (m⁻¹) in Cockburn Sound (2008-2014). Station locations are shown by filled circles. Values for Northern Harbour (NH3, 0.15 m⁻¹) and Mangles Bay (MB, not available) are not included.
Figure 5.6. Bathymetry (left panel) and spatial variation in fraction of surface light reaching the seabed in Cockburn Sound (2008-2014) (right panel). Areas where less than 10% of light reaches the seabed are masked in white.

5.2 Comparison between Cockburn Sound and Warnbro Sound

The nutrient concentration measured at a selected number of monitoring sites within Cockburn Sound during 2008-2014, was compared with sites of similar water depth in Warnbro Sound, in order to highlight any major differences between the two (Figure 5.7). For this purpose, two shallow (~2 m) sites (MB and WSSB), and three deep (~20 m) sites (CS5, CS13, and WS4) were identified. The largest difference between Cockburn Sound and Warnbro Sound, for both total nitrogen and phosphorus, was between the two shallow coastal sites at Mangles Bay (MB) and Safety Bay (WSSB) respectively (Figure 5.7). Total nutrient levels in the central basin of Warnbro Sound (WS4) were very similar to those measured at the northern perimeter of Cockburn Sound (CS5), with concentrations in the southern deep water of Cockburn Sound (CS13) moderately elevated with respect to both of them.
6 Temporal patterns and trends

6.1 Dependence and Independence among water quality parameters

The usefulness of time series or between year comparisons will depend somewhat on the extent to which parameters are correlated with each other or where there is a seasonal trend within years. As such we undertook a series of exploratory data analyses to determine these dependences.

6.1.1 Correlations among parameters

Significant relationships existed among several of the water quality parameters measured (Table 6.1) and many of these are expected dependencies. For example Light attenuation and chlorophyll $a$ are directly related (Figure 6.1) because as chlorophyll $a$ increases in the water column it acts to restrict light penetration. Similarly, chlorophyll $a$ and Total Nitrogen (Figure 6.2) are related as nitrogen is usually the limiting nutrient in marine waters. In fact the relationships between parameters are quite complex and we don’t attempt to explain them all here but when we look for trends in parameters over time it is important to keep in mind the interdependencies that exist between them.
### Correlation matrix (Pearson):

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<th>TOT_NIT</th>
<th>SURF_TEMP</th>
<th>BOT_TEMP</th>
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<th>Light (kd)</th>
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<td></td>
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<td>-0.359</td>
<td>-0.332</td>
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<td>0.169</td>
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### Coefficients of determination ($R^2$):

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<td>CHLORO 'a'</td>
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### p-values:

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Table 6.1. Correlation matrix and probability values for water quality parameters from Cockburn Sound and Warnbro Sound from 1566 samples collected between 2008/08 to 2013/14. Samples with any parameter missing were not included in the analyses and significance was determined using Bonferroni levels of significance (alpha/number of comparisons = 0.05/21 = 0.002). Significant levels of correlation shown in bold type.
Figure 6.1. Relationship between chlorophyll a and Light attenuation for water quality parameters from Cockburn Sound and Warnbro Sound from 1566 samples collected between 2008/08 to 2013/14.

Figure 6.2. Relationship between Total Nitrogen and chlorophyll a for water quality parameters from Cockburn Sound and Warnbro Sound from 1566 samples collected between 2008/08 to 2013/14.
6.1.2 Within year dependencies

A noticeable feature of some of the water quality parameters was a within year trend. That is, over the 15-16 weekly samples that were taken each year, some parameters showed consistent seasonal variation from December to March. This is not unexpected for some parameters. For example there is a seasonal cycle in temperature in Cockburn Sound.

This seasonal cycle in water temperature is evident in the example illustrated below from Site CS5 (Figure 6.3). Chlorophyll \( \alpha \) can also vary over the time course of sampling within a year as shown in Figure 6.4. However, we cannot expect there to be the same seasonal response in every year as illustrated in Figure 6.5 which shows how the seasonal trend in chlorophyll \( \alpha \) at Site CS5 varies in each year while still showing an increase between December and March.

![Figure 6.3. Variation in surface water temperature at Site CS5 between December 2012 and March 2013.](image)
Because of these within-year or seasonal patterns, analysing change over time in the water quality parameters is not as straightforward as just comparing how mean values change at each site from year to year. Nevertheless such comparisons are a useful way of visualising the overall patterns of a data set, especially over longer periods. So for the short term analysis (2008/09 to 2013/14) we have approached our time series analysis by providing box plots of each site over time (Section 7) as well as analyses of covariance which can detect differences in the value of parameters while taking into account seasonal patterns if they exist. For the longer time series (1982/83 to 2013/14), there is a
much greater range in the value of water quality parameters so we are less concerned about within-year variation. So for these data we have presented box plots of the time series at each site (Section 7) and a method of time series analysis called “regime shift detection” which is commonly applied to time series of climate data and reveals step changes or sustained state changes in parameters over time. Identifying these sustained changes either up or down in parameters can be useful in evaluating whether a management response has taken effect or to point to some changed circumstance that may have caused a baseline to shift. Each of these approaches is described in greater detail below.

### 6.1.3 Effect of long term changes acting globally

Changes in Cockburn Sound also need to be considered in the context of global climate change which may influence the area independent of any local environmental variation or anthropogenic impacts. To examine for any long term changes that might be related to climate change we examined the 29 year record of surface and bottom temperature at sites C4 and C5 which are those sites closest to the open ocean for which the long term data was available. Only March data was analysed to avoid the confounding effect of seasonal variation described above. March was chosen as the effect of climate change in south-western Australia involves a lengthening of the warm season and this is when the climate change signal is most pronounced (Caputi et al. 2009).

Temperature records for the two sites were combined and the long term average for both surface and bottom temperature was calculated and subtracted from each observations. This resulted in a set of temperature anomalies which were analysed using regression analysis against time (years from the first observation).

The temperature anomalies were found to increase significantly over time for both surface (p=0.00015) and bottom (p=0.00013) temperatures. Rates of increase in temperature were 0.0325 °C per year for surface temperatures (95% confidence interval (CI) ± 0.016 °C) and 0.0295 °C per year (95% CI ± 0.014 °C) for bottom water (Figure 6.6). These rates of change are very similar to other such studies in Western Australia (e.g. Pearce et al. 2007; Caputi et al. 2009).

![Figure 6.6. Plot of March temperature anomaly from surface (left) and bottom (right) water samples from 1985 to 2014.](image-url)
6.2 Recent short-term patterns and trends (2008-2014)

Analyses of Covariance (ANCOVA) enable us to compare changes in water quality parameters over time (between-years) and between-sites in a way which takes into account the types of seasonal or within-year changes described above in section 6.1.

For each of the parameters listed below we have provided:

1. A graph of the dataset plotted over the sampling season (number of days after November 30), with all years plotted together, to examine for inherent seasonal or within-year patterns consistent across all years.

2. An analysis of covariance table which gives the probabilities of:
   - a significant seasonal or within year trend in the data,
   - a significant difference in the parameter between years
   - a significant difference in the parameter between sites

3. A graph of annual means of the parameter showing which years are significantly different from other years.

4. A graph of means of the parameter over six years at each sampling site showing which sites are significantly different from other sites.

All statistical comparisons were made using $\alpha = 0.001$ to guard against type 1 errors given the large sample sizes, large number of comparisons and lack of normality in datasets. This is 50 times more rigorous than used in most studies, and while this may result in some type 2 errors, it means we can focus on discussion of the most significant patterns.

Where relevant we have compared the mean values of water quality parameters to environmental quality thresholds or “trigger” values specified for southwest in Australia National Water Quality Management Strategy produced by the Australia and New Zealand Environment and Conservation Council (ANZEEC 2000) and to local thresholds or Environmental Quality Guideline (EQG) values developed by the Western Australian Environmental Protection Authority (EPA 2015). The EQGs take into account local conditions and the value of water quality parameters monitored at the Warnbro Sound Reference site (see EPA 2015 for detailed methodology). EQGs are reviewed annually by the Cockburn Sound Management Council. Different EQGs are applied to Areas of High Protection and Moderate Protection within Cockburn Sound (see Fig. 4.2).

We have applied the 2013/14 EQGs in comparing site averages over the 2008/09 – 2013/14 six year period. In some cases we have concluded that individual sites did not exceed that EQG. This does not mean that individual sites may not have exceeded the EQG that was in place for that site in any one year.

For example, we conclude below that no sites exceeded the 2013/14 EQGs for temperature when comparing the six year means for all sites up until 2013/14 against that EQG. However Mohring and Rule (2013) found that with the heatwave event in 2011, some sites in 2011 and 2012 did exceed the local EQG that was in place for those years.
In their study, Mohring and Rule (2013) were concerned with trying to identify site and year specific exceedances which might help explain changes in seagrass shoot density at some sites. Our purpose is more related to analysing the recent short term and longer term historical trends in water quality parameters and whether these are tracking toward or away from levels favourable to improved ecosystem health.

6.2.1 Total Nitrogen
Total Nitrogen did not vary seasonally over the period of summer/autumn sampling (p=0.336, Table 6.2) and only 6 or 0.3 % of samples were above the ANZECC trigger value of 230 µgN/l (Figure 6.7).

Significant differences in Total Nitrogen were detected between years with 2009/10 (143 µgN/l) being significantly higher than other years (116 – 136µgN/l) (Figure 6.8). The most recent years 2012/13 and 2013/14 were significantly lower than other years indicating a favourable trend over the 6 year period.

Northern Harbour (NH3) and Mangles Bay (MB) (both 172 µgN /l) had the highest levels of mean Total Nitrogen, while CBH grain terminal site CS10N had the next highest at 139 µgN /l (Figure 6.9). These three sites were significantly higher than all other sites where depth integrated samples were taken.

The two deeper sites in Cockburn Sound (CS13) and Warnbro Sound (WS4) where bottom water samples are also taken had higher levels of Total Nitrogen (138 and 146 µgN /l respectively) in the bottom water than either surface or depth integrated samples (Figure 6.9). This is not unusual as lower levels of light at depth restrict phytoplankton growth and uptake of nutrients.

![Figure 6.7. Plot showing Total Nitrogen levels at all sites from 2008/09 to 2013/14. The trend line is a linear fit and the slope is not significantly different from 0 (p=0.336) indicating there is no seasonal trend in Total Nitrogen. The ANZECC trigger value for inshore marine waters is shown.](image-url)
<table>
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<tr>
<th>Source</th>
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Table 6.2. Type III Analysis of Covariance table for Total Nitrogen.

Figure 6.8. Plot showing annual change in mean Total Nitrogen at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0001 in all cases).
Figure 6.9. Plot showing mean Total Nitrogen levels at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.0009 in all cases).
6.2.2 Total Phosphorus

Total Phosphorus did not vary seasonally over the period of summer/spring sampling (p=0.360, Table 6.3) and 156 or 7.1% of samples were above the ANZECC trigger value of 20 µgP/l (Figure 6.10).

Significant differences in mean Total Phosphorus were detected between years with 2010/11 through to 2012/13 (15.4-16.5 µgP/l) being significantly higher than other years (12.1 – 13.6 µgP/l) (Figure 6.11).

Northern Harbour (NH3) (17.8 µgP /l, 19% of samples exceeding ANZECC limit) and Mangles Bay (MB) (19.2 µgP /l, 31%) had the highest levels of Total Phosphorus along with the two Kwinana Beach sites CS9A (BP oil refinery) (17.1 µgP /l, 17%) and CS10N (CBH grain terminal) (17 µgP /l, 21%).

The two deeper sites in Cockburn Sound (CS13) and Warnbro Sound (WS4) where bottom water samples are also taken had higher levels of Total Phosphorus in the bottom water than either surface or depth integrated samples (Figure 6.12). This is not unusual as lower levels of light at depth restrict phytoplankton growth and uptake of nutrients.

![Graph showing Total Phosphorus levels at all sites from 2008/09 to 2013/14. The trend line is a linear fit and the slope is not significantly different from 0 (p=0.363) indicating there is no seasonal trend in total phosphorus. The ANZECC trigger value for inshore marine waters is shown.](image)

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Table 6.3. Type III Analysis of Covariance table for Total Phosphorus.
Figure 6.11. Plot showing annual change in mean Total Phosphorus at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0001 in all cases).

Figure 6.12. Plot showing mean Total Phosphorus levels at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.0008 in all cases).
6.2.3 Nitrogen/Phosphorus ratio

Mean Total Nitrogen to Total Phosphorus ratios ranged between 8.1 and 10.9 for all sites (Figure 6.15) and did not vary seasonally (p=0.163, Table 6.4). Only 432 or 19.7% of samples did not exceed the Redfield ratio of 16:1 for N:P uptake by phytoplankton (here calculated as a mass ratio with 7.24 being the equivalent ratio when considering TN:TP) (Figure 6.13). This indicates an excess of nitrogen in the water column on almost 80% of samples. It is interesting to note that surface samples from Warnbro Sound (WS4 Top) were significantly higher than all other sites (Figure 6.15). The only sites with mean ratios above 10 were in Warnbro Sound (WS4 and WSSB). The annual change in N:P ratios were more marked with 2009/10 (TN:TP ratio=12.5) being significantly higher than all other years (Figure 6.14). This is consistent with 2009/10 having significantly lower Total Phosphorus (Figure 6.11) and significantly higher Total Nitrogen (Figure 6.8) than other years.

![Figure 6.13. Plot showing ratios of Total Nitrogen to Total Phosphorus at all sites from 2008/09 to 2013/14. The trend line is a linear fit and the slope is not significantly different from 0 (p=0.163) indicating there is no seasonal trend in the ratio. The Redfield ratio of N:P uptake by phytoplankton of 7.24:1(mass ratio equivalent to 16:1 molar ratio) is shown.](image)

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Table 6.4. Type III Analysis of Covariance table for ratios of Total Nitrogen to Total Phosphorus.
Figure 6.14. Plot showing annual change in mean ratios of Total Nitrogen to Total Phosphorus at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0002 in all cases). The Redfield ratio of N:P uptake by phytoplankton of 7.24:1 (mass ratio equivalent to 16:1 molar ratio) is shown.

Figure 6.15. Plot showing mean ratios of Total Nitrogen to Total Phosphorus at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.0009 in all cases). The Redfield ratio of N:P uptake by phytoplankton of 7.24:1 (mass ratio equivalent to 16:1 molar ratio) is shown.
6.2.4 Temperature of surface water

As is to be expected there was a strong seasonal signal in surface water temperature with temperatures in January and February warmer than those in December and March (Table 6.5, Figure 6.16). The 2010/11 mean of 24 °C (Figure 6.17) was significantly warmer than other years (p<0.0001) and this is consistent with the well documented marine heat wave which occurred in early 2011 (e.g. Pearce et al. 2011). 2008/09 (22.7 °C) was significantly cooler than all other years. Northern Harbour (NH3) (24.2 °C) was the warmest site and along with the Kwinana Power Station site (CS12) (23.6 °C) they were significantly warmer than all other sites sampled (Figure 6.18). The reasons for this are not clear, although reduced water flow at NH3 relative to other sites is likely to be a factor. Six year means did not exceed the 2013/14 Environmental Quality Guidelines (EQG) for Cockburn Sound (24.2 °C for High Protection Areas and 24.4 °C for Moderate Protection Areas) at any site.

Figure 6.16. Plot showing surface seawater temperature at all sites from 2008/09 to 2013/14. The trend line is a polynomial fit and there is a significant seasonal trend (p<0.0001).

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Table 6.5. Type III Analysis of Covariance table for surface water temperatures.
Figure 6.17. Plot showing annual change in mean surface water temperatures at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0001 in all cases).

Figure 6.18. Plot showing mean surface water temperatures at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.0004 in all cases). Environmental Quality Guidelines (EQG) for Cockburn Sound for both High Protection Areas (HPA) and Moderate Protection Areas (MPA) are shown. Refer to EPA (2015) for details of how EQGs for Cockburn Sound are determined.
6.2.5 Temperature at seabed

Water temperatures at the seabed showed similar patterns to those at the surface with a strong seasonal trend (p < 0.0001, Table 6.6, Figure 6.19) and with 2010/11 being the warmest year and 2008/09 the coolest (Figure 6.20). While there were significant differences between sites (Figure 6.21) with the Kwinana Power Stations sites (CS9 and CS12) being the warmest, these two sites were not significantly different from the next 12 warmest ranked sites (Figure 6.21). Six year means did not exceed the 2013/14 Environmental Quality Guidelines (EQG) for Cockburn Sound (24.2 °C for High Protection Areas and 24.4 °C for Moderate Protection Areas) at any site.

![Figure 6.19. Plot showing bottom seawater temperature at all sites from 2008/09 to 2013/14. The trend line is a polynomial fit and there is a significant seasonal trend (p<0.0001).](image)

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*Table 6.6. Type III Analysis of Covariance table for bottom water temperatures.*
Figure 6.20. Plot showing annual change in mean bottom water temperatures at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0001 in all cases).

Figure 6.21. Plot showing mean bottom water temperatures at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.0009 in all cases). Environmental Quality Guidelines (EQG) for Cockburn Sound for both High Protection Areas (HPA) and Moderate Protection Areas (MPA) are shown. Refer to EPA (2015) for details of how EQGs for Cockburn Sound are determined.
6.2.6 Dissolved oxygen at seabed

As we have seen earlier (Table 6.1), there is a strong negative correlation between dissolved oxygen (DO) levels and sea water temperature at the sea bed, and this was borne out again in this analysis (Table 6.7) with the lowest levels of DO occurring in February (Figure 6.22). The most recent years of 2012/13 and 2013/14 had the highest levels (6.9 mg/l) (Figure 6.23) and sites SF (near the causeway) and WSSB (Warnbro Sound) had significantly higher levels of DO (7.3 mg/l) than any other site (Figure 6.24).

![Figure 6.22. Plot showing bottom dissolved oxygen levels at all sites from 2008/09 to 2013/14. The trend line is a polynomial fit and there is a significant seasonal trend (p<0.0001).](image)

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Table 6.7. Type III Analysis of Covariance table for bottom dissolved oxygen levels.
Figure 6.23. Plot showing annual change in mean bottom dissolved oxygen levels at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0001 in all cases).

Figure 6.24. Plot showing mean bottom dissolved oxygen levels at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.001 in all cases).
6.2.7  Light attenuation

The level of light attenuation increased slightly but significantly between December and March (p<0.0001, Table 6.8, Figure 6.25) and this is to be expected given the same seasonal increase in chlorophyll a levels (Figure 6.28). 156 or 9.9% of light attenuation values were above the ANZECC guidance level of 0.13 per meter. However most of these occurrences were at the Northern Harbour site NH3 (65) and the James Point sites 9 and 9A (31). 2010/11 and 2011/12 had the highest levels of light attenuation (lowest light) (Figure 6.26). Northern Harbour (NH3) had by far the lowest light levels reaching the seabed and this was significantly different from all other sites. Warnbro Sound (WS4) and the northern Cockburn Sound site (CS4) had the highest light levels (Figure 6.27). Local Environmental Quality Guideline (EQG) values for light attenuation are 0.09 per meter (High Protection Areas [HPA]) and 0.11 per meter for Moderate Protection Areas [MPA]) (EPA 2015). Only CS11 and CS13 in the southern HPA exceeded the EQG and Northern Harbour (NH3) was the only MPA area to exceed the EQG (Fig. 6.27).

![Figure 6.25. Plot showing light attenuation levels at all sites from 2008/09 to 2013/14. The trend line is a linear fit and the slope is significantly different from 0 (p<0.0001) indicating there is a significant seasonal trend.](image)

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Table 6.8. Type III Analysis of Covariance table for light attenuation.
Figure 6.26. Plot showing annual change in mean light attenuation at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0004 in all cases).

Figure 6.27. Plot showing mean light attenuation at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.0008 in all cases). Environmental Quality Guidelines (EQG) for Cockburn Sound for both High Protection Areas (HPA) and Moderate Protection Areas (MPA) are shown. Refer to EPA (2015) for details of how EQGs for Cockburn Sound are determined.
6.2.8 Chlorophyll a

There was a significant increasing trend in chlorophyll a between December and March (p<0.0001, Table 6.9) and 65% of all samples exceeded the ANZECC trigger value of 0.7 µg/l and 26% exceeded this by more than double the trigger value (Figure 6.28). 2011/12 had significantly higher mean chlorophyll a (1.5 µg/l) than the other years except 2010/11 (1.4 µg/l) (Figure 6.29). Northern Harbour (NH3) had the mean highest chlorophyll a of any site (4.1 µg/l) and 97% of all samples exceeded the ANZECC trigger value by three times (2.1 µg/l). Sites with mean chlorophyll a levels more than double the ANZECC trigger value were eastern shore and southern Cockburn Sound sites (MB, CS9, CS9A, CS10N, CS11 and CS13) and between 42% and 53% of all samples at these sites exceeded the ANZECC trigger value of 0.7 µg/l by more than double (Figure 6.30). However, only five sites exceeded the 2013/14 Environmental Quality Guideline (EQG) values for Cockburn Sound. Three High Protection Area (HPA) sites, Mangles Bay (MB), CS11 and CS13, all of which are in the southern HPA exceeded the local chlorophyll a EQG of 0.9 µg/l (Fig. 6.30). Two Moderate Protection Areas (MPA), Northern Harbour (NH3) and Kwinana Bulk Jetty (CS9A) exceeded the local chlorophyll a EQG of 1.5 µg/l (Fig. 6.30).

![Figure 6.28. Plot showing chlorophyll a levels at all sites from 2008/09 to 2013/14. The trend line is a linear fit and the slope is significantly different from 0 (p<0.0001) indicating there is a significant seasonal trend. The ANZECC trigger value for inshore marine waters is shown.](image)

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Table 6.9. Type III Analysis of Covariance table for chlorophyll a.
Figure 6.29. Plot showing annual change in mean chlorophyll a at all sites from 2008/09 to 2013/14. The letters above each mean indicate which means are significantly different from or equal to each other (i.e. A>B>C, p<0.0002 in all cases).

Figure 6.30. Plot showing mean chlorophyll a at each site for all 2008/09 to 2013/14 samples combined. The letters above each mean indicate which means are significantly different from each other (i.e. A>B>C, p<0.0001 in all cases). Environmental Quality Guidelines (EQG) for Cockburn Sound for both High Protection Areas (HPA) and Moderate Protection Areas (MPA) are shown. Refer to EPA (2015) for details of how EQGs for Cockburn Sound are determined.

6.3.1 Time series analyses

The length of the time series analysis that could be undertaken at each site depended on the number of years that had been sampled. Broadly these fell into two categories:

1982-2014 (with some gap years) – Sites CS4, CS5, CS6&CS6A, CS7, CS8, CS9, CS10&CS10N and CS11
2002-2014 (most parameters) – Sites G1, G2, G3, CB, NH3, SF, WS4 and WSSB

The time series analysis was undertaken using the sequential t-test analysis of regime shift (STARS) (Rodionov 2004; Rodionov and Overland 2005). An add-in for MS Excel for this test (STARS software v2.1) is available at [www.BeringClimate.noaa.gov](http://www.BeringClimate.noaa.gov). This analysis detects where there has been a sustained change in a parameter. This “shift point” separates sustained periods of “stable means” and specifies a level of significance for each shift point.

The test can fail to detect the correct timing of a shift where there is a true gradual trend associated with a gradual change in a parameter. It is common for water quality data to show gradual changes, especially over short periods. However, out of 77 tests of parameter versus site with 65 shift points detected we only found 9 such failures. In these cases the shift point was manually determined. Because the test is also conservative (cut off length set at 5 years, p<0.05), it can also miss shift points in the last couple of years of a time series. Again of 77 tests we found just 2 such cases and these shift points were manually determined. In assessing the results of the tests we only recognised shift points significant at the α = 0.05 level. All shift points are shown on the graphs accompanying these analyses. Significant shifts are shown with a black arrow, non-significant shifts are indicated as “NS” and manually assigned shift points are indicated with a dotted line arrow. Where relevant detection limits or ANZECC trigger values or guidance values are shown on the graphs.

6.3.1.1 Dissolved Inorganic Nitrogen (DIN)

Dissolved Inorganic Nitrogen or DIN is the most readily utilisable source of nitrogen for phytoplankton and algae. Unlike in freshwater systems where phosphorus may be limiting for plant growth marine system are usually nitrogen limited and when harmful algal blooms occur in the marine environment, it is usually excessive anthropogenic nitrogen that is to blame. Therefore DIN is a key indicator of water quality in near shore coastal environments such as Cockburn Sound. The DIN was calculated from the sum of ammonium-N (NH$_4$-N) and nitrate+nitrite-N (NO$_x$-N). If both NH$_4$-N and NO$_x$-N were less than the detection limit then they were set to 1 µgN/l and if either NH$_4$-N or NO$_x$-N were less than the detection limit then parameter less than detection was set to zero and the DIN concentration calculated.

In Cockburn Sound, DIN levels were very high prior to 1990 and subsequent to this there have been two major reductions (Figure 6.32). In 1993 there were four sites that showed a shift change in DIN from stable means of 15-40 µgN/l down to 10 µgN/l or less (Figure 6.31 and Figure 6.32). The next major shift was in 2007 when 13 sites showed a reduction in DIN from stable means of about 8 µgN/l to below ANZECC trigger values (5 µgN/l) and to below detection limits. These patterns were
consistent on the north, eastern and western parts of Cockburn Sound and it is interesting to note that prior to 2007 both the Warnbro Sound sites had DIN levels of about 8-9 µgN/l which is well above the ANZECC trigger value and the trend at both Warnbro Sound sites follows those in Cockburn Sound with a dramatic reduction in 2007 (Figure 6.32).

Even though DIN levels are now stable well below the ANZECC trigger levels, they may still vary in biologically meaningful ways and consideration should now be given to changing the analytical methods for ammonium and nitrite/nitrate to lower detection limits.

Figure 6.31. Number of significant shifts by year in the stable mean of DIN for sites in Cockburn Sound and Warnbro Sound. These are based on the figures shown in Figure 6.32.

Figure 6.32 (following 2 pages). Mean values and regime shifts in the stable mean for DIN at sites in Cockburn Sound and Warnbro Sound. ANZECC trigger levels and detection limits for DIN are shown on the graphs. Black arrows indicate statistically significant shifts in the stable mean, NS indicate non-significant shifts and dotted black arrows indicate a manual selection of a shift point (see section 6.3.1 for explanation of methods).
6.3.1.2  **Total Nitrogen (TN)**

Total nitrogen includes both inorganic and organic forms as well as nitrogen tied up in living and dead organic matter. Prior to 1990 TN exceeded ANZECC trigger values of 230 µgN/l at all sites (Figure 6.34). There was a shift change at six sites between 1990 and 1993 (Figure 6.33) after which time all sites monitored at that time were below the ANZECC trigger value. When the newer series of sites began to be monitored in 2001-2002, the only site which exceeded the ANZECC trigger value for TN was NH3 (Northern Harbour). The next major shift in TN occurred in about 2006 when 7 sites showed a significant shift (Figure 6.33) down to levels of about 120 µgN/l (Figure 6.34). TN levels at NH3 remain elevated relative to other sites at about 180 µgN/l, but are still well below the ANZECC trigger value. Concentration levels and shifts in the stable means of TN were similar in Cockburn Sound and Warnbro Sound (Figure 6.34).

![Figure 6.33](image-url)  
*Figure 6.33. Number of significant shifts by year in the stable mean of Total Nitrogen for sites in Cockburn Sound and Warnbro Sound. These are based on the figures shown in Figure 6.34.*

![Figure 6.34](image-url)  
*Figure 6.34 (following 2 pages). Mean values and regime shifts in the stable mean for Total Nitrogen (TN) at sites in Cockburn Sound and Warnbro Sound. ANZECC trigger levels for TN are shown on the graphs. Black arrows indicate statistically significant shifts in the stable mean, NS indicate non-significant shifts and dotted black arrows indicate a manual selection of a shift point (see section 6.3.1 for explanation of methods).*
6.3.1.3 Total Phosphorus

Total Phosphorus (TP) exceeded ANZECC trigger value of 20 µgP/l at all sites prior to about 2000 when there was a significant shift in 8 sites between 1998 and 2001 (Figure 6.35) from 30-40 µgP/l down to 15-20 µgP/l (Figure 6.36). After 2002 there were no shifts in stable means with all sites (Cockburn Sound and Warnbro Sound) having TP concentrations of about 12-14 µgP/l except NH3 (Northern Harbour) which was about 18 µgP/l (Figure 6.36).

Figure 6.35. Number of significant shifts by year in the stable mean of Total Phosphorus (TP) for sites in Cockburn Sound and Warnbro Sound. These are based on the figures shown in Figure 6.36

Figure 6.36 (following 2 pages). Mean values and regime shifts in the stable mean for Total Phosphorus (TP) at sites in Cockburn Sound and Warnbro Sound. ANZECC trigger levels for TP are shown on the graphs. Black arrows indicate statistically significant shifts in the stable mean, NS indicate non-significant shifts and dotted black arrows indicate a manual selection of a shift point (see section 6.3.1 for explanation of methods).
6.3.1.4 Light Attenuation

Stable means of light attenuation levels varied considerably across sites in Cockburn Sound from less than 0.09 m$^{-1}$ at G3 near the northern end of Garden Island to more than 0.14 m$^{-1}$ at NH3 in Northern Harbour. Light attenuation was lowest and hence the water most clear at WS4 in Warnbro Sound (less than 0.08 m$^{-1}$). In general the graphs in Fig. 6.38 show an improving trend in light attenuation since about 2000, however the variability from year to year is very high so few significant range shifts were detected (Figure 6.37 and Figure 6.38) despite significant improvements at several sites around 2006. Light attenuation at Moderate Protection Area (MPA) sites CS6A, CS7, CS9, CS10N and High Protection Area (HPA) sites CS5 and CS8 have all moved below the 2013/14 MPA Environmental Quality Guidelines (EQG) for Cockburn Sound since about 2006. Six sites showed a possible more recent shift (reduction) in 2013 and three of these were significant (CS5, CS8, G1) but it is too early to say if these are sustained improvements in water clarity. ANZECC provide guidance on target water clarity for both inshore waters (0.09-0.13 m$^{-1}$) like Cockburn Sound as well as offshore waters (0.05-0.08 m$^{-1}$). These values are marked on the graphs and show that all sites in Cockburn Sound except NH3 (Northern Harbour) are within the expected range for unmodified inshore waters (0.09-0.13 m$^{-1}$).

Figure 6.37. Number of significant shifts by year in the stable mean of light attenuation for sites in Cockburn Sound and Warnbro Sound. These are based on the figures shown in Figure 6.38.

Figure 6.38. (following 2 pages) Mean values and regime shifts in the stable mean for light attenuation at sites in Cockburn Sound and Warnbro Sound. ANZECC guidance levels for light attenuation and 2013/14 Cockburn Sound Environmental Quality Guideline (EQG) values for High Protection Areas (HPA) and Moderate Protection Areas (MPA) are shown on the graphs. Black arrows indicate statistically significant shifts in the stable mean, NS indicate non-significant shifts and dotted black arrows indicate a manual selection of a shift point (see section 6.3.1 for explanation of methods).
The diagrams illustrate the trend of light attenuation (m⁻¹) over the years from 1980 to 2020 for different sites.

- **Top Left:** CS5 Light and Mean, showing data for various years with ANZECU Upper limit of inshore water.
- **Top Right:** CS4 Light and Mean, with similar data and comparison with ANZECU Upper limit inshore water.
- **Bottom Left:** CS6&6A Light and Mean, showing data with ANZECU Upper limit offshore water.
- **Bottom Right:** CS8 Light and Mean, with data for ANZECU Upper limit offshore water.

Each diagram includes a blue line for CS Light, a red line for Mean, and a horizontal yellow line representing the ANZECU Upper limit for the respective water type.
6.3.1.5 Chlorophyll $a$

Chlorophyll $a$ levels at all sites are at or exceed the ANZECC trigger value (0.7 µg/l). Sites along the eastern shore were historically high (around 2.5 µg/l), higher than sites in the middle of Cockburn Sound or near Garden Island. Site CS10 showed a significant increase in 1992, however during the 1995-2000 period most Sites reduced to around the 1 µg/l or less. Chlorophyll $a$ in Northern Harbour (NH3) remains very high (about 4 µg/l).

Five sites, including three of those along the eastern shoreline showed significant improvement in chlorophyll $a$ levels in 2005 (Fig. 6.39) with these shifts taking the stable means for those sites within the 2013/14 MPA Environmental Quality Guidelines (EQG) for Moderate Protection Area (MPA) sites in Cockburn Sound.

A significant shift (increase) in chlorophyll $a$ occurred in 2011 at WS4 in Warnbro Sound (Figure 6.39) to above the ANZECC trigger value for the first time since 2003 (Figure 6.40). The same happened at G3. These may warrant investigation as these sites would be expected to most closely resemble an unmodified condition.

![Figure 6.39. Number of significant shifts by year in the stable mean of chlorophyll $a$ for sites in Cockburn Sound and Warnbro Sound. These are based on the figures shown in Figure 6.40.](image-url)

![Figure 6.40. (following 2 pages) Mean values and regime shifts in the stable mean for chlorophyll $a$ at sites in Cockburn Sound and Warnbro Sound. ANZECC trigger levels and 2013/14 Cockburn Sound Environmental Quality Guideline (EQG) values for High Protection Areas (HPA) and Moderate Protection Areas (MPA) for chlorophyll $a$ are shown on the graphs. Black arrows indicate statistically significant shifts in the stable mean, NS indicate non-significant shifts and dotted black arrows indicate a manual selection of a shift point (see section 6.3.1 for explanation of methods).](image-url)
7 Box plots of data at all sites and years

Due to the large quantity of data (>5700 samples) box plots were used to present the nitrogen, phosphorus and chlorophyll a concentration data on a per site basis. The large differences in concentration observed between 1982/83 and 2013/14 also prompted the presentation of the data in three time intervals 1982/83 to 2013/14, 1996/97 to 2013/14 and 2007/2008 to 2013/14. Where possible the concentration scales were kept the same between the sites, though some exceptions apply. Box plots use percentiles and the mean to describe the variability of the data. Below in Figure 7.1 is a key describing how to interpret the box plots. In addition to the water quality data the box plots also contain the detection limits for each of the analysis (as per Table 4.2) and the ANZECC (2000) trigger values for inshore marine ecosystems in south-west Australia to serve as references. Since samples which registered non-detects were assigned half the detection limit, the box plot falls below the detection limit in many years.

The following parameters are shown in each box plot; ammonium, as nitrogen (NH$_4$-N), nitrate + nitrite, as nitrogen (NO$_x$-N), total nitrogen (TN), filterable reactive phosphorus (FRP), total phosphorus (TP) and chlorophyll a (Chl A).

Also note that in each figure below the data in each box plot which represent each summer sampling period are labelled with the year the majority of the data was collected in, e.g. 2011 represents samples taken between 1 Dec 2010 and 31 Mar 2011.

While temporal trends have been explored in Sections 5 and 6 the box plots in Figure 7.2 to Figure 7.48 show that along with decreasing concentrations the variability (spread of data) has also reduced over time.

![Figure 7.1. Key for interpreting box plots](image_url)
Figure 7.2 Box plot for site CS4 (1982/83 to 2013/14)

Figure 7.3 Box plot for site CS4 (1996/97 to 2013/14)
Figure 7.4 Box plot for site CS4 (2007/08 to 2013/14)

Figure 7.5 Box plot for site CS5 (1982/83 to 2013/14)
Figure 7.6 Box plot for site CS5 (1996/97 to 2013/14)

Figure 7.7 Box plot for site CS5 (2007/08 to 2013/14)
Figure 7.8 Box plot for site CS6/CS6A (1982/83 to 2013/14)

Figure 7.9 Box plot for site CS6/CS6A (1996/97 to 2013/14)
Figure 7.10 Box plot for site CS6/CS6A (2007/08 to 2013/14)

Figure 7.11 Box plot for site CS7 (1982/83 to 2013/14)
Figure 7.12 Box plot for site CS7 (1996/97 to 2013/14)

Figure 7.13 Box plot for site CS7 (2007/08 to 2013/14)
Figure 7.14 Box plot for site CS8 (1982/83 to 2013/14)

Figure 7.15 Box plot for site CS8 (1996/97 to 2013/14)
Figure 7.16 Box plot for site CS8 (1982/83 to 2013/14)

Figure 7.17 Box plot for site CS9 (1982/83 to 2013/14)
Figure 7.18 Box plot for site CS9 (1996/97 to 2013/14)

Figure 7.19 Box plot for site CS9 (2007/08 to 2013/14)
Figure 7.20 Box plot for site CS10/CS10N (1982/83 to 2013/14)

Figure 7.21 Box plot for site CS10/CS10N (1996/97 to 2013/14)
Figure 7.22 Box plot for site CS10/CS10N (2007/08 to 2013/14)

Figure 7.23 Box plot for site CS11 (1982/83 to 2013/14)
Figure 7.24 Box plot for site CS11 (1996/97 to 2013/14)

Figure 7.25 Box plot for site CS11 (2007/08 to 2013/14)
Figure 7.26 Box plot for site CS12 (1996/97 to 2013/14)

Figure 7.27 Box plot for site CS12 (2007/08 to 2013/14)
Figure 7.28 Box plot for site CS13 (2007/08 to 2013/14)

Figure 7.29 Box plot for site CB (1996/97 to 2013/14)
Figure 7.30 Box plot for site CB (2007/08 to 2013/14)

Figure 7.31 Box plot for site CS9A (1996/97 to 2013/14)
Figure 7.32 Box plot for site CS9A (2007/08 to 2013/14)

Figure 7.33 Box plot for site G1 (1996/97 to 2013/14)
Figure 7.34 Box plot for site G1 (2007/08 to 2013/14)

Figure 7.35 Box plot for site G2 (1996/97 to 2013/14)
Figure 7.36 Box plot for site G2 (2007/08 to 2013/14)

Figure 7.37 Box plot for site G3 (1996/97 to 2013/14)
Figure 7.38 Box plot for site G3 (2007/08 to 2013/14)

Figure 7.39 Box plot for site MB (2007/08 to 2013/14)
Figure 7.40 Box plot for site NH3 (1996/97 to 2013/14)

Figure 7.41 Box plot for site NH3 (2007/08 to 2013/14)
Figure 7.42 Box plot for site SC (1996/97 to 2013/14)

Figure 7.43 Box plot for site SF (1996/97 to 2013/14)
Figure 7.44 Box plot for site SF (2007/08 to 2013/14)

Figure 7.45 Box plot for site WS4 (1996/97 to 2013/14)
Figure 7.46 Box plot for site WS4 (2007/08 to 2013/14)

Figure 7.47 Box plot for site WSSB (1996/97 to 2013/14)
Figure 7.48 Box plot for site WSSB (2007/08 to 2013/14)
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9 References


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