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Baseline water quality of the Jurien Bay Marine Park: a benchmark for warm temperate Western Australia?

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ABSTRACT

Spatial and seasonal nutrient dynamics were examined at three locations in the coastal waters of the Jurien Bay Marine Park (JBMP), to establish a quantitative baseline for water quality in this park. Nutrient concentrations were typically low across all sampling periods. Differences between locations were apparent for some variables, while few differences were found between nearshore, lagoonal and offshore sampling sites. Concentrations of most nutrients tended to be highest during autumn and lowest during spring, but there were significant interactions between season, location and site for almost all parameters measured, suggesting an inconsistent effect of these factors. The findings reported here are likely to be a result of two major processes: 1) the onset of autumn/winter storms that detach macroalgae and seagrass and transport it onshore, where it decays and releases nutrients back into the water column; and 2) the synergistic effects of reduced nutrient supply during spring and increased macroalgal growth assimilating significant quantities of nutrients during this period. The JBMP represents a relatively unimpacted example of marine water quality in warm temperate Western Australia. Given that there are mechanisms for actively managing inputs into these waters into the future, these data could provide a suitable benchmark for assessing water quality management targets for biogeographically similar coastal waters where water quality may have been degraded from anthropogenic activities.

Keywords: water quality, nutrient, Western Australia, baseline

INTRODUCTION

Many coastal marine ecosystems are becoming increasingly degraded by anthropogenic pressures such as fishing, direct physical damage by boats and people, the introduction of non-indigenous species, contamination by pollutants and nutrient enrichment (Gray 1997). Of particular concern to naturally oligotrophic (i.e. low nutrient status) coastal waters is the problem of nutrient enrichment, which may be a significant environmental stressor in coastal areas adjacent to urban and industrial centres and/or those subject to discharge from agricultural catchments (Gorgula & Connell 2004; Gorman et al. 2009). The impacts of enrichment can be localised, such as those commonly related to urban effluent outfalls, or diffuse and widespread, such as the impacts from catchment degradation adjacent to the Great Barrier Reef in north-eastern Australia (Moss et al. 2005). Unchecked nutrient enrichment can lead to responses in the form of, for example, algal blooms and changes in benthic community structure (Gorgula & Connell 2004) or, in extreme cases, the loss of organisms due to hypoxia (e.g. Anderson et al. 2002).

Oceanic waters adjacent to warm temperate Western Australia are typically oligotrophic and nitrogen-limited, which is largely a consequence of the relatively warm, southwards-flowing Leeuwin current and a lack of significant upwelling along the coast (Weaver & Middleton 1989; Johannes et al. 1994; Hanson et al. 2005). Annual rainfall in this area is also relatively low, resulting in limited nutrient transport into coastal waters from terrestrial sources. This marine environment is, however, characterized by high biodiversity and endemism (Phillips 2001; Roberts et al. 2002) and since the 1980s a system of marine protected areas (MPAs) has been established to protect marine biodiversity in the coastal waters of south-west Western Australia.

Integral to the effective management of MPAs is the long-term monitoring of key ecological assets and the pressures that act on them (Fancy et al. 2008). Rigorously documented benchmark measures are required to understand long-term trends in asset condition, and to avoid 'shifting baseline syndrome', whereby perceptions of 'normal' resource condition alter over time in response

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to long-term, and typically gradual, ecosystem degradation (Sheppard 1995). Such incremental changes to inshore marine water quality may occur near industrial and/or population centres that are subject to sustained anthropogenic impacts from, for example, industrial and municipal discharges and catchment inflows over many decades.

Despite such potential impacts, these areas may still support a range of high biodiversity conservation values, and many MPAs are located in close proximity to such areas of high human use. In Western Australia, for example, the Marmion and Shoalwater Islands Marine Parks are located close to the Perth metropolitan area, and coastal industrial infrastructure and oceanic wastewater outfalls discharge within, or near, both of these MPAs (Oceanica Consulting 2010). Under specific weather conditions, Marmion Marine Park is also subject to discharge from the significantly degraded catchment of the Swan–Canning River system (Brearley 2005). Given this context, it is possible that baseline values of water quality for such 'urban' MPAs are, or eventually will be, confounded by such impacts.

In contrast, the Jurien Bay Marine Park (JBMP) is located along Western Australia's relatively remote mid-west coast. Although 200 km north of the Perth area, this marine environment is biogeographically similar (Commonwealth of Australia 2006), but is subject to fewer and less intense environmental stressors. The adjacent hinterland is sparsely populated with no major towns, and there are limited impacts from terrestrial run-off and agricultural activity (Department of Conservation and Land Management 2005). The primary aim of this study was to establish baseline water quality conditions for the coastal waters of the JBMP. Given the relatively remote location of this marine park, we anticipated that anthropogenic nutrient enrichment of these coastal waters would be low and we further sought to assess whether these data could also provide benchmark values for water quality in biogeographically similar, but possibly impacted, coastal waters in warm temperate south-western Australia.

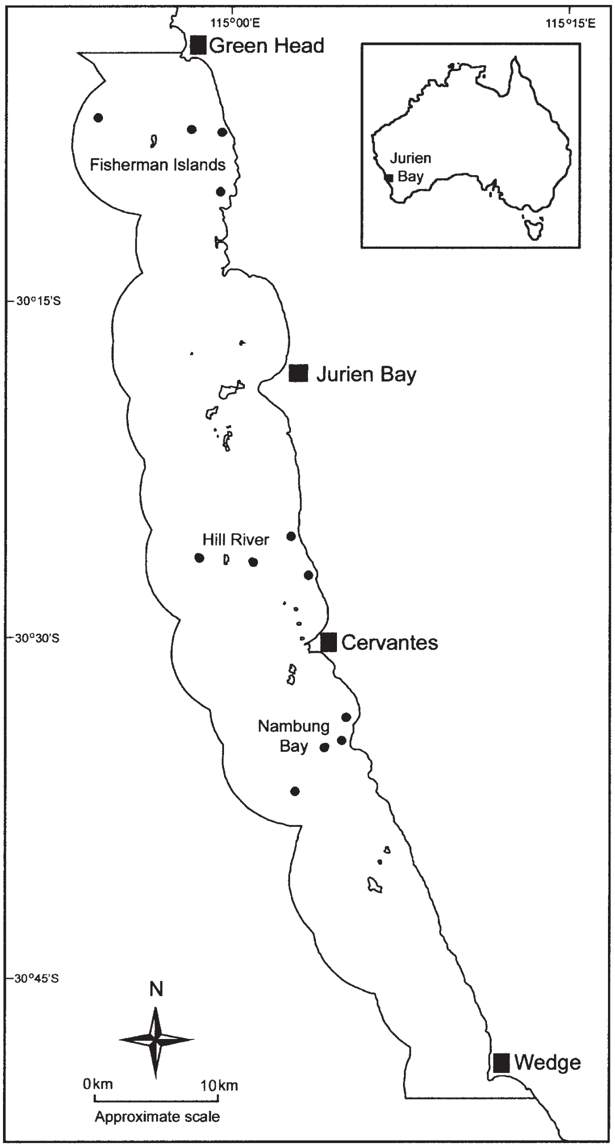

Figure 1. The Jurien Bay Marine Park. Sampling sites (black dots) were adjacent to Fisherman Islands, Hill River and Nambung Bay.

METHODS

This study was conducted in the JBMP on the central west coast of Western Australia (Fig. 1). The study area is not subject to major anthropogenic pollutant or riverine discharges, and the circulation of nearshore marine waters is primarily wind-driven (Sanderson 2000). The region's complex seabed topography is characterized by limestone barrier reefs and emergent rocks and islands that lie parallel to the coast inshore from the 20 m depth contour. These structures form inshore lagoons that are relatively sheltered from oceanic swell. Corresponding with coastal bathymetric features, water sampling sites were identified as nearshore sheltered, nearshore exposed, lagoon and offshore. While both nearshore sheltered and exposed sites were located close to the shore in depths of typically <5 m, exposed sites differed in being directly adjacent to openings in the barrier reef system and could thus be expected to be subject to greater wave action and mixing than the relatively protected sheltered sites. Lagoon sites were located midway between the shore and the barrier reef system in depths of 6–8 m, whereas offshore sites were located in oceanic waters >20 m deep outside the reef.

The full set of sampling sites was established at each of three locations: Fisherman Islands (30° 07' S, 114° 56' E), Hill River (30° 23' S, 115° 03' E) and Nambung Bay (30° 32' S, 115° 05' E) in the JBMP (Fig. 1). Within each site, three independent replicate samples were collected (see below). All sites within a location were sampled on a single day (i.e. over three days for all locations) during the austral summer (December to February), autumn (March to May), winter (June to August) and spring (September to November) of 2004, and samples were collected as close as was possible to the middle of each season. In order to examine finer-scale temporal variation, monthly samples were collected across the year from each site in the Hill River location.

Temperature (°C), salinity (ppt) and dissolved oxygen (mg L^{-1}) were measured at each site using either a YSI Inc. (Yellow Springs, Ohio, USA) 6600 SDL recorder or a YeoKal Electronics (Brookvale, New South Wales, Australia) model 602 temperature/salinity bridge. Both instruments were laboratory-calibrated before field use. Physical parameters were recorded at approximately 20 cm depth intervals through the water column and these values were averaged to provide an integrated value for each site. Prior to integration of water column values, data were examined to determine the level of difference between surface and bottom values. In general, differences were larger during summer than the other seasons; however, in all cases these differences were negligible. For instance, the maximum difference in temperature between surface and bottom waters at a single site (Fisherman Islands nearshore exposed) was 1.3 °C, but in general, the difference was less than 0.5 °C. Differences in salinities and dissolved oxygen concentrations were similarly small.

At each site, three 20 L water samples were collected, which comprised equal volumes of water collected ca. 1 m from both the surface and the seabed. Water was only collected mid-depth when sites were <3 m deep. Samples were collected with a submersible pump or with a 10 L Niskin bottle when depths exceeded 15 m. Sampling equipment was thoroughly pre-rinsed at each site and the pump was run for two minutes prior to sample collection to purge the previous sample. An equal measured volume of water from surface and bottom samples was mixed and filtered to 1.2 μm and the GF/C (Whatman glass microfiber filter) filter papers were wrapped in another filter paper and stored. A second sub-sample was then drawn through a 45 μm cellulose nitrate syringe filter and stored in two 10 mL tubes; one for analysis and the second as a contingency. All samples were stored on ice in the field and frozen within 12 hours until laboratory analysis.

Water from the 10 mL sample was analysed for ammonium (NH_4^+) by the alkaline phenate method (Switala 1993), nitrate/nitrites (NO_x) by the copper-cadmium reduction method (Johnson & Petty 1983) and orthophosphate (OP) by the ascorbic acid method (Johnson & Petty 1982) using a Lachal Quick Chem 8000 Automated Flow Injection Analyser. Filter papers were stored in the dark for 24 hours at 4 °C, after which chlorophyll-*a* (Chl-*a*) was extracted by grinding in 90% acetone and measured using a Varian Cary 50 Spectrophotometer (Greenburg et al. 1992). This method does not detect plankton <0.8 μm in diameter. The concentration of Chl-*a* was measured to a resolution of 0.1 μg L^{-1}, while NH_4^+ was measured to a resolution of 3.00 μg L^{-1} and NO_x and OP were measured to a resolution of 2.00 μg L^{-1}.

For the seasonal dataset, concentrations of NH_4^+, NO_x, OP and Chl-*a* were analysed using a three-factor (season, location and site) analysis of variance (ANOVA) with GMAV5 (Underwood et al. 1998). For all tests, season and site were considered to be fixed factors while location was designated as a random factor. In addition, monthly data from the Hill River location were examined using a two-factor ANOVA with month and site designated as fixed factors. For graphical and analytical purposes, data that were below the limits of laboratory resolution (i.e. below detectable limits, BDL) were designated to be 0.5 of that limit (Australian and New Zealand Environment and Conservation Council 2000). However, substituting values is not recommended where >25% of values are BDL (Australian and New Zealand Environment and Conservation Council 2000), as was the case for NH_4^+ in spring where all values were BDL. These data were removed from the analysis and only comparisons between the remaining seasons were performed. Prior to analysis, all data were checked to meet the assumption of homogeneity of variances using Cochran's test (Underwood 1997) and data were appropriately transformed to correct heterogeneity where this assumption was violated. Where significant ($\alpha < 0.05$) results were returned for the main fixed effects (season and site) multiple comparisons were made using the Student–Newmans–Keuls test.

RESULTS

Mean temperature varied significantly across seasons (ANOVA; $f_{3, 44} = 106.07$, $p < 0.001$) and ranged from an average of 17.09 ± 0.37 °C during winter to 23.47 ± 0.19 °C during summer (Table 1). Mean salinity also varied significantly across seasons (ANOVA; $f_{3, 44} = 461.30$, $p < 0.001$) and ranged between 34.16 ± 0.05 ppt and 36.41 ± 0.03 ppt, with the maximum mean value recorded during summer (Table 1). Values for dissolved oxygen were only recorded during summer and autumn, and there was no difference between these seasons (Table 1).

Nutrient concentrations were typically low across all seasons (Table 1). With the exception of ammonium, the mean concentration of nutrients was highest in samples collected during autumn and lowest in samples collected in spring (Table 1, Fig. 2). The effects of the main factors of season, location and site are discussed below, but for all parameters, the highest-order interactions (season × location × site) were significant, suggesting that sites were affected differently across locations and seasons.

The concentration of NH_4^+ was low but variable across all locations and seasons except spring, where all values were BDL (<3 μg L^{-1}; Table 1, Fig. 2). Concentrations BDL were recorded during each season, while the maximum concentration (10 μg L^{-1}) was recorded from the nearshore sheltered site at Nambung Bay during autumn (Table 1). There were no significant differences in mean NH_4^+ concentrations between seasons (Table 2). Overall, the concentration of NH_4^+ was significantly higher at Nambung Bay than at either Fishermans Islands or Hill River; however, the effect of season within locations was not consistent (Table 2). For example, mean concentrations were significantly lower in spring than all other seasons across all locations, but at Fisherman Islands, summer values were significantly higher than winter and autumn values, while at Hill River, winter values were

Table 1

Summary of minimum, maximum and mean (±SE, n = 9) concentrations (µg L^{-1}) for water quality parameters measured in each site. Overall ranges and means for temperature, salinity and dissolved oxygen are also given.

	Summer	Autumn	Winter	Spring
NH$_4^+$				
Nearshore sheltered	3.00–9.00 (4.67 ± 0.58)	<3.00*–10.00 (3.39 ± 0.95)	<3.00*–6.00 (3.94 ± 0.44)	<3.00*
Nearshore exposed	<3.00*–5.00 (3.39 ± 0.49)	<3.00*–3.00 (2.33 ± 0.26)	<3.00*–7.00 (3.00 ± 0.63)	<3.00*
Lagoon	<3.00*–4.00 (3.11 ± 0.34)	<3.00*–4.00 (2.94 ± 0.39)	<3.00*–6.00 (4.11 ± 0.56)	<3.00*
Offshore	3.00–5.00 (3.44 ± 0.24)	<3.00*–4.00 (2.53 ± 0.33)	<3.00*–7.00 (3.53 ± 0.50)	<3.00*
NO$_x$				
Nearshore sheltered	2.00–5.00 (3.33 ± 0.33)	2.00–8.00 (4.33 ± 0.76)	<2.00*–4.00 (3.00 ± 0.29)	2.00–4.00 (3.00 ± 0.17)
Nearshore exposed	3.00–5.00 (3.44 ± 0.24)	<2.00*–6.00 (3.56 ± 0.53)	2.00–6.00 (3.33 ± 0.47)	2.00–5.00 (3.00 ± 0.33)
Lagoon	2.00–4.00 (3.11 ± 0.26)	3.00–9.00 (5.78 ± 0.78)	3.00–7.00 (4.78 ± 0.49)	2.00–5.00 (3.22 ± 0.28)
Offshore	3.00–4.00 (3.11 ± 0.11)	3.00–7.00 (4.83 ± 0.41)	3.00–7.00 (5.06 ± 0.49)	2.00–3.50 (2.56 ± 0.19)
OP				
Nearshore sheltered	5.00–7.00 (6.00 ± 0.17)	6.00–8.00 (6.78 ± 0.22)	3.00–5.00 (4.11 ± 0.26)	4.00–6.00 (5.00 ± 0.17)
Nearshore exposed	5.00–7.00 (5.89 ± 0.31)	6.00–8.00 (7.00 ± 0.29)	3.00–5.00 (4.11 ± 0.31)	5.00–6.00 (5.33 ± 0.17)
Lagoon	6.00–7.00 (6.33 ± 0.17)	6.00–8.00 (7.22 ± 0.22)	3.00–6.00 (4.22 ± 0.32)	5.00–8.00 (5.67 ± 0.33)
Offshore	7.00–8.00 (7.22 ± 0.15)	6.50–7.00 (6.83 ± 0.08)	3.00–5.00 (3.83 ± 0.19)	4.00–6.00 (5.56 ± 0.23)
Chl-*a*				
Nearshore sheltered	0.30–0.50 (0.36 ± 0.02)	0.40–1.10 (0.69 ± 0.08)	0.20–0.30 (0.24 ± 0.02)	<0.10*–0.20 (0.09 ± 0.02)
Nearshore exposed	0.20–0.40 (0.28 ± 0.02)	0.30–0.50 (0.41 ± 0.03)	0.10–0.30 (0.27 ± 0.02)	<0.10*–0.20 (0.09 ± 0.02)
Lagoon	0.10–0.30 (0.20 ± 0.02)	0.20–0.40 (0.27 ± 0.02)	0.20–0.30 (0.22 ± 0.01)	<0.10*–0.10 (0.08 ± 0.01)
Offshore	0.10–0.40 (0.24 ± 0.03)	0.25–0.50 (0.34 ± 0.03)	0.40–0.65 (0.52 ± 0.03)	0.10–0.20 (0.17 ± 0.01)
Temperature (ºC)	21.46–25.24 (23.47 ± 0.19)	21.08–22.31 (21.63 ± 0.07)	15.20–19.66 (17.09 ± 0.37)	17.97–20.10 (19.12 ± 0.18)
Salinity (ppt)	36.03–36.73 (36.41 ± 0.03)	35.89–36.24 (35.99 ± 0.02)	33.9–34.50 (34.16 ± 0.05)	35.02–35.55 (35.34 ± 0.05)
DO (mgL^{-1})	5.76–7.47 (6.80 ± 0.08)	5.39–8.13 (7.20 ± 0.09)	No data	No data
DO (% saturation)	85.82–107.18 (98.52 ± 0.93)	74.86–115.17 (100.71 ± 1.28)	No data	No data

* = measured to the lowest limit of resolution

significantly higher than both autumn and summer values. (Table 2).

The concentration of NO$_x$ was generally BDL (<2 µg L^{-1}) in the nearshore sheltered site during winter, while the maximum value (9 µg L^{-1}) was recorded from the lagoon site at Nambung Bay during autumn (Table 1). In general, the concentration of NO$_x$ was highest in autumn; however, this pattern was not observed in samples from all locations, with samples from Hill River having the highest concentration during winter (Fig. 2, Table 2). The mean concentration of NO$_x$ was significantly higher at Nambung Bay than Fisherman Islands, while concentrations from Hill River were significantly lower than both of these locations. No significant differences were returned for the tests between seasons or sites (Table 2). In general, concentrations of NO$_x$ in samples collected from Nambung Bay were significantly higher across all sites than at either Fisherman Islands or Hill River; there was no significant difference between locations for samples collected from nearshore sheltered sites.

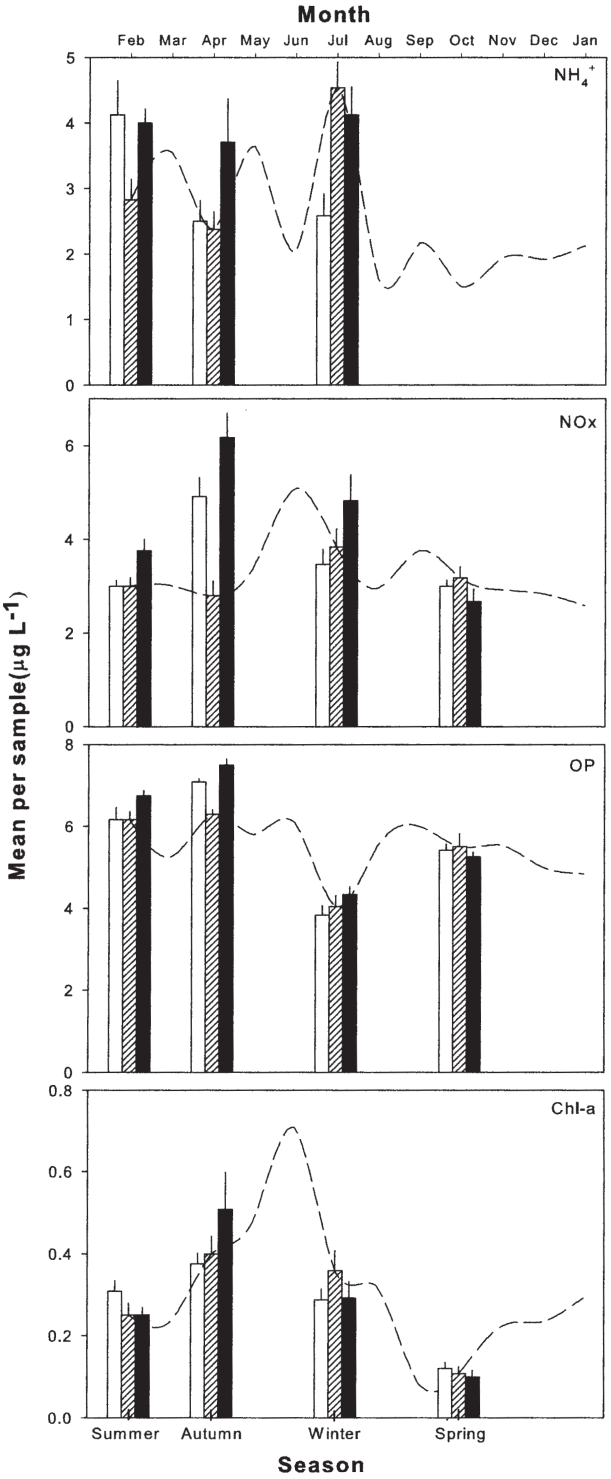

*Figure 2. Mean (±SE, n = 12) concentrations of: a) NH_4^+; b) NO_x; c) OP; d) Chl-*a *in water samples collected at Fisherman Islands (unfilled bars), Hill River (hatched bars) and Nambung Bay (filled bars) during each season of 2004. Monthly means collected at the Hill River transect are also included (dotted line).*

The concentration of OP ranged from a minimum of 3 μg L^{-1} in a number of samples collected during winter to a maximum of 8 μg L^{-1} collected in each of the other seasons (Table 1). The mean concentration of OP was generally higher during autumn than any other season, with the exception of offshore sites where the concentration was highest in summer (Table 1). Analysis of variance revealed a difference between seasons (Table 2) with the mean OP concentration in winter (4.07 ± 0.13 μg L^{-1}) being significantly lower than any other season, and the mean OP concentration in autumn (6.96 ± 0.11 μg L^{-1}) being significantly higher than both summer (6.36 ± 0.13 μg L^{-1}) and spring (5.39 ± 0.12 μg L^{-1}). Overall, there was a difference between locations, with concentrations from Nambung Bay being significantly higher than both Fisherman Islands and Hill River (Table 2). This pattern was not seen in spring when concentrations from Nambung Bay were significantly lower than both Fisherman Islands and Hill River. Differences between sites were not consistent across locations. For example, at both Hill River and Nambung Bay, nearshore sheltered samples had significantly lower values than any other sites; however, at Fisherman Islands, nearshore sheltered samples had significantly higher concentrations of OP than both nearshore exposed and lagoon samples.

The concentration of Chl-*a* ranged from BDL (<0.1 μg L^{-1}) in a number of samples collected from spring to a maximum of 1.1 μg L^{-1} in samples collected from the nearshore sheltered site at Nambung Bay during autumn (Table 1). The mean concentration of Chl-*a* was typically below 0.5 μg L^{-1} in all seasons, locations and sites (Table 1). Analysis of variance revealed significant differences for all comparisons except for the test between locations (Table 2). Overall, the mean concentration of Chl-*a* was significantly lower in spring (0.11 ± 0.01 μg L^{-1}) than in all of the other seasons. Mean concentrations in summer (0.27 ± 0.15 μg L^{-1}) and winter (0.31 ± 0.02 μg L^{-1}) were also significantly lower than those in autumn (0.43

Table 2

Summary of the three-factor ANOVA conducted on ammonium (NH_4^+), nitrate/nitrites (NO_x), orthophosphate (OP) and chlorophyll-*a* (Chl-*a*) concentration. The test for ammonium did not include data from spring where concentrations were all below the detectable limit. *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$.

			All other parameters			
Source of variation	**df**	**NH_4^{+a}**	**df**	**NOx**	**OP^a**	**Chl-*a***
Season (Se)	2	-	3	-	***	**
Location (L)	2	***	2	***	***	-
Site (Si)	3	-	3	-	-	**
Se x L	4	***	6	***	*	***
Se x Si	6	-	9	-	-	**
L x Si	6	-	6	*	***	***
Se x L x Si	18	***	18	**	*	***
Error	72		96			

^{a} data $sqrt_{(x+1)}$ transformed

Table 3

Summary of the two-factor ANOVA examining concentrations of ammonium (NH_4^+), nitrate/nitrites (NO_x), orthophosphate (OP) and chlorophyll-*a* (Chl-*a*) across months at a single site. *** = $p < 0.001$; ** = $p < 0.01$; * = $p < 0.05$.

Source of variation	df	NH_4^{+a}	NOx^a	OP^a	Chl-*a*^{a}
Month (Mo)	11	***	ns	***	***
Site (Si)	3	ns	ns	***	***
Mo x Si	33	*	**	ns	***
Error	96				

^{a}data $\log_{(x+1)}$ transformed

± 0.04 μg L^{-1}); however, this was not consistent between locations. In most sites, the mean concentration of Chl-*a* was lowest during spring and highest during autumn (Table 1, Fig. 2); however, at the offshore sites mean Chl-*a* concentration was highest in winter (Table 1). Significant differences between sites were only returned for Chl-*a* (Table 2) where mean concentrations at nearshore sheltered (0.35 ± 0.04 μg L^{-1}) and offshore (0.32 ± 0.03 μg L^{-1}) sites were significantly higher than at lagoon sites (0.19 ± 0.01 μg L^{-1}; Table 1).

The analyses of nutrient concentrations collected from the Hill River transect revealed significant differences between months for NH_4^+, OP and Chl-*a* and between sites for OP and Chl-*a* (Table 3, Fig. 2). For both Chl-*a* and NO_x, the maximum mean concentrations were recorded in June, while for OP and NH_4^+, maximum mean concentrations were recorded during April and July, respectively. The timing of the minimum mean concentrations was different for each parameter: NO_x in January, OP in April, Chl-*a* in September, and NH_4^+ in October (Fig. 2) A significant interaction between month and site was also found for all parameters except OP (Table 3).

DISCUSSION

This study demonstrated that the coastal waters of the JBMP have a relatively depauperate nutrient regime. The concentration of all chemical parameters measured was consistently low across seasons and months, with mean values ranging from BDL (for NH_4^+ and NO_x) to 7.22 ± 0.22 μg L^{-1} for OP. In contrast, background levels of nutrients in other locations at similar latitudes are considerably higher. For example, coastal waters around the east and west coast of South Africa have mean OP values ranging between 20 to 40 μg L^{-1}, while management target values for NH_4^+ are set at 20 μg L^{-1} (Department of Water Affairs and Forestry 1995). While this outcome conforms to expectations regarding south-western Australia's typically oligotrophic warm temperate marine environment, these data will form an important baseline against which to measure future water quality in the JBMP.

Other studies support these findings by illustrating the generally oligotrophic nature of coastal waters in this region. For example, mean (±SE) concentrations of ammonium, nitrate-nitrite and filterable reactive phosphorous (orthophosphate) of 5 ± 3, 4 ± 1 and 6 ± 1 μg L^{-1}, respectively were recorded in Cockburn and Warnbro Sounds (immediately south of Perth) by Wilson and Paling (2006). Water quality monitoring over 13 years (1986–2009) at reference sites for the Perth Ocean Outlet in Marmion Marine Park (adjacent to Perth) found that mean summer concentrations of Chl-*a* ranged between 0.2–0.75 μg L^{-1}, while dissolved inorganic nitrogen (DIN) ranged between 6.75–21.1 μg L^{-1} (Oceanica Consulting, unpublished data). This study also found that mean summer Chl-*a* and DIN concentrations ranged from 0.06–0.42 μg L^{-1} and 2.64–7.33 μg L^{-1}, respectively, at reference sites for the Sepia Depression Ocean Outfall (west of Garden Island). These data indicate that while reference sites in Marmion Marion Park may have slightly elevated concentrations of both Chl-*a* and DIN, the Sepia Depression values are much closer to those recorded in this study at the JBMP. The typically low nutrient levels in coastal waters of south-west Western Australia are maintained by broad-scale down-welling of surface waters caused by the Leeuwin Current and prevailing onshore winds (Weaver & Middleton 1989; Hanson et al. 2005). Consequently, these marine habitats are characterised by relatively high benthic productivity and macroalgal growth.

Despite an a priori expectation that differences in nutrient concentration would be observed between sites, this was generally not found in the current study, although there were usually significant interactions with location. Nutrient levels in nearshore environments were anticipated to be higher than other sites as a result of the influence of factors such as rainfall and terrestrial run-off (Johannes et al. 1994), groundwater flows (Johannes 1980), nearshore productivity and the accumulation and the decay of shoreline algal wrack (Crossland et al. 1984; Kirkman & Kendrick 1997). Such accumulations of wrack can be common during winter in waters of south-west Western Australia (Kirkman & Kendrick 1997) and can provide a significant nutrient resource (Crawley & Hyndes 2007). However, the lack of elevated nutrients at lagoon and nearshore sites observed during this study suggested that either: 1) sufficient flushing or mixing was occurring to disperse nutrients that may have derived from such sources; or 2) that assimilation of nutrients by macrophytes (seaweeds and seagrasses) in these habitats was rapid. As these waters are generally oligotrophic and marine plants are nutrient-limited, the rapid assimilation of nutrients is a more likely explanation (Cambridge & Hocking 1997).

While the concentrations of most nutrients measured during this study were low overall, they did typically differ between locations. This result is not altogether surprising as many authors have reported spatial variation in coastal nutrient parameters across scales from metres to kilometres (Elsdon & Connell 2009), and such differences are generally attributed to localised oceanographic conditions (Gibbs 2000; Hanson et al. 2005; Lourey & Kirkman 2009) or differences in the rate of supply (Gorman et al. 2009). In general, samples from Nambung Bay had higher nutrient concentrations than those from other locations, although this pattern was not consistent across seasons. It is currently unclear what is driving the elevated nutrient concentrations at this location; however, it may be that waters adjacent to Nambung Bay are receiving higher inputs of nutrients than at other locations.

Similarly, although identifying seasonal patterns was not the primary aim of this study, some patterns were evident in these data. Concentrations of Chl-*a* and OP were significantly higher in autumn than any other season. This finding is generally consistent with previous studies in this region, which have found higher nutrients levels during winter months in coastal waters of the Perth region and in shallow waters of the Houtman Abrolhos Islands, which are north of the JBMP (Crossland et al. 1984; Johannes et al. 1994; Lourey & Kirkman 2009). This peak in nutrient concentration may result from large volumes of macroalgae and seagrass being removed and transported onshore by winter storm activity (Kirkman & Kendrick 1997), where it breaks down through wave action and/or biological decay and is and recycled back into the water column. While wave action in the JBMP is typically greatest in winter, mean maximum wave height during the current study was actually highest in the autumn months (Western Australian Department of Transport, unpublished data), and the peak of some nutrients recorded here may be a result of storm activity during that time.

In addition to the autumn peaks in concentration, there was a trend for most parameters to be lowest in spring. Most notably, NH_4^+ was BDL at all locations and sites during this season. Despite the oligotrophic nature of Western Australian coastal waters, shallow benthic macroalgal and seagrass assemblages display exceptionally high rates of primary productivity, with the dominant habitat-forming kelp *Ecklonia radiata* producing as much as 20.7 kg-wet-wt m^{-2} per annum (Kirkman 1984, 1989), while the seagrass *Posidonia sinuosa* produces 30–50% of the *E. radiata* value (Cambridge & Hocking 1997). Kelp reaches its maximum rate of productivity during spring as solar irradiance intensifies and water temperatures begin to increase (Kirkman 1984). It is possible that the low level of nutrients reported here, and particularly that of nitrogenous compounds, which are limiting to plant growth, may be a result of the synergistic effects of: 1) the decreased accumulation and breakdown of macroalgae over spring (see above), resulting in lower nutrient supply; and 2) the assimilation of these compounds by marine plants during this period of rapid growth.

In demonstrating that the nutrient content of these coastal waters is generally low, we propose that this study has broader significance than simply providing a benchmark for future monitoring in the JBMP. Given the relative lack of anthropogenic impacts on marine water quality in the JBMP, we suggest that the outcomes of this study could have long-term relevance as a reference for water quality in biogeographically similar areas of Western Australia that have been subjected to sustained anthropogenic impacts. While water quality adjacent to the Perth metropolitan area is currently broadly comparable with that of the JBMP, continuing pressure from urban and industrial growth (e.g. Gorgula & Connell 2004) and associated increases in outfall discharges and catchment inflows means that background marine nutrient levels in these areas may rise. Under such circumstances, and in the continuing absence of similar broadly-based and sustained impacts in the JBMP, it is probable that the water quality of this area will continue to approximate that of the marine waters in the Perth area prior to such long-term influences. Given that there is a statutory framework for managing and controlling inputs into the JBMP that does not exist in many other areas, background water quality will be maintained in a near-pristine state into the future. Hence, waters of the JBMP are likely to have increasing significance as a regional 'unimpacted' reference site for the coastal water quality of south-west Western Australia.

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