Technical Report

Adelaide Coastal Waters Study

***Stage 2** Research Program 2003 – 2005*

Technical Report No. 15   August 2006

Assessment of the effects of inputs to the Adelaide coastal waters on the meadow forming seagrasses, Amphibolis *and* Posidonia*.*

Task EP 1 Final Technical Report

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Assessment of the effects of inputs to the Adelaide coastal waters on the meadow forming seagrasses, Amphibolis *and* Posidonia*. Task EP 1 Final Technical Report.*

Simon Bryars, Greg Collings, Sasi Nayar, Grant Westphalen, David Miller, Emma O'Loughlin, Milena Fernandes, Gen Mount, Jason Tanner, Rachel Wear, Yvette Eglinton, and Anthony Cheshire.

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Executive overview

Background

Since the 1940s, over 5000 ha of seagrasses have been lost from the Adelaide metropolitan coastline. In particular, major losses of the nearshore meadow forming seagrasses, *Amphibolis* and *Posidonia*, have occurred in Holdfast Bay with a gradual offshore regression of the 'blue-line.' Prior to European settlement, there were very few coastal inputs to Holdfast Bay. While the Patawalonga Creek and the Port River may have historically delivered some freshwater to the coast, engineering works and urbanisation during the 20th century substantially increased coastal inputs via rivers, stormwater drains, and wastewater treatment plant (WWTP) outfalls. Due to the various coastal inputs, Holdfast Bay is no longer pristine, with elevated levels of nutrients, toxicants, and turbidity being detected and reported regularly over the last 30 years. Consequently, each of these potential stressors has been implicated in the historical loss of seagrasses. In addition, it is possible that reduced salinity associated with the freshwater coastal inputs has also contributed to seagrass loss.

Task EP 1 of the Adelaide Coastal Waters Study

The Adelaide Coastal Waters Study (ACWS) is a major, multi-institutional study aimed at developing knowledge and tools to enable the sustainable management of Adelaide's coastal waters by identifying causes of ecosystem modifications and the actions required to halt and reverse the degradation. The ACWS region extends from Port Gawler in the north to Sellicks Beach in the south, but does not specifically include the Port River/Barker Inlet system. The ACWS comprises six separate, but linked, research tasks. In an attempt to better understand causal mechanisms of seagrass loss, Task EP 1 "Assessment of the effects of inputs to the Adelaide coastal waters on seagrass ecosystems and key biota" was developed with four key objectives:

1. To determine the current status of coastal water, sediment and seagrass quality
2. To determine nutrient fluxes in seagrasses
3. To determine effects of nutrients on seagrasses
4. To determine effects of other stressors on seagrasses.

In order to address the four objectives of Task EP 1, a series of desktop, laboratory and field activities was undertaken between 2003-2006, with the results detailed in six technical reports by Westphalen *et al.* (2004, 2005), Bryars *et al.* (2006), Collings *et al.* (2006a,b), and Nayar *et al.* (2006). The present report summarises the outcomes of the six Task EP 1 technical reports as they pertain to the four key objectives outlined above. It also provides conclusions (in conjunction with outcomes of technical reports from other ACWS tasks) regarding the effects of four key stressors on *Amphibolis* and *Posidonia* that were identified in the first of the Task EP 1 technical reports (see Westphalen *et al.* 2004) as being potential causes of major seagrass loss along the Adelaide coastline, viz.:

- toxicants
- salinity
- turbidity
- nutrients

Causes of historical seagrass loss

With regard to the major objective of Task EP 1, which was to better understand causal mechanisms of broad-scale seagrass loss off Adelaide, the following conclusions have been drawn relating to the four potential stressors of toxicants, salinity, nutrients, and turbidity:

Toxicants

Toxicants were unlikely to have been responsible for broad-scale historical seagrass losses because:

- Toxicants have only been sporadically detected in very low concentrations in freshwater entering Adelaide's coastal waters (Wilkinson *et al.* 2005a, Bryars *et al.* 2006).
- Concentrations required to affect seagrass physiological processes are relatively high (Westphalen *et al.* 2004), and due to rapid dilution in the marine environment (see Pattiaratchi *et al.* 2006), the historical levels detected in stormwater could never have reached levels capable of having an impact.
- Bryars *et al.* (2006) found all toxicants to be undetectable in the coastal waters off Adelaide following peak stormwater flows when detection would be most likely.
- Bryars *et al.* (2006) found very low or undetectable levels of potential toxicants in marine sediment samples collected adjacent to major stormwater outlets where they are most likely to occur, and at offshore sites where terrestrially derived sediments may potentially be transported.

Salinity

Reduced salinity from stormwater and wastewater was unlikely to have been responsible for broad-scale historical seagrass losses because:

- Both *Amphibolis antarctica* and *Posidonia sinuosa* adult plants are highly tolerant to short-term (72 hours) reductions in salinity (Westphalen *et al.* 2005).
- Major reductions in salinity for prolonged periods (weeks) are required to kill adult *A. antarctica* and *P. sinuosa*.
- In the nearshore region where stormwater enters Adelaide's coastal waters and at locations adjacent to wastewater outfalls, reductions in salinity are only minor (Kaempf 2005, Bryars *et al.* 2006, Pattiaratchi *et al.* 2006)

However, short-term reductions in salinity can affect *A. antarctica* seedlings and *P. sinuosa* fruits. Thus, it is possible that stormwater and wastewater could influence recruitment processes on a very localised scale.

Turbidity

Increased turbidity from stormwater could have contributed to broad-scale historical losses of nearshore seagrass because:

- Since at least the 1930s, turbid stormwater discharges have entered Holdfast Bay (Wilkinson *et al.* 2005a, Bryars *et al.* 2006).
- Hydrodynamic modelling indicates that coastal inputs to Holdfast Bay tend to be entrained in the nearshore region (Pattiaratchi *et al.* 2006).
- A series of light loggers moored for one year during 2005-2006 in Holdfast Bay showed that during periods of stormwater flows, nearshore seabed light conditions were drastically reduced (Collings *et al.* 2006b).
- Physiological modelling using field data indicates that, under certain scenarios, light levels across the 12-month period were sufficiently low to cause the death of *Amphibolis* at 3m depth but not at deeper depths (Collings *et al.* 2006b). Furthermore, it is highly likely that nearshore light conditions were worse during the 1940s to 1960s (when much of the nearshore seagrass loss occurred, Westphalen *et al.* 2004), because discharges from the Torrens River were significantly greater than today (Wilkinson 2005).

While we cannot determine whether the light climate alone might have been the cause of the loss of inshore seagrass, the possibility cannot be discounted on the basis of the Task EP 1 work, and at the very least, the poor light climate in nearshore Holdfast Bay will provide an extra stress on the seagrass beds over and above any other stressors.

Nutrients
Increased nutrients from stormwater and wastewater could have been responsible for broad-scale historical seagrass losses because:

- Since at least the 1970s, elevated levels of water column nutrients have occurred in Holdfast Bay and at other localised areas associated with wastewater outfalls (Bryars *et al.* 2006). Unnatural nutrient inputs to Holdfast Bay would have commenced as early as the 1930s when the Torrens River was diverted to the sea, the Glenelg WWTP began operating (Wilkinson *et al.* 2003, 2005a), and the Penrice Soda factory began operating in the Port River (EPA 2006).
- Results of a nitrogen stable isotope survey clearly indicate that the existing offshore seagrasses from Port Gawler to Port Noarlunga do receive nitrogen sourced from WWTP and industrial outfalls, viz. Penrice, (Bryars *et al.* 2006) that have been operating for many decades (Wilkinson *et al.* 2003, Wilkinson *et al.* 2005b). Clearly then, nearshore seagrasses (prior to their loss) would also have been exposed to those same nutrient sources.
- Results of a major long-term field experiment unambiguously proved that chronic, yet minor increases in water column nutrients (as might be associated with WWTP and industrial inputs) could cause the slow decline of *Amphibolis* and *Posidonia* in shallow, previously nutrient-poor coastal waters (Collings *et al.* 2006a). These results support the ‘nutrient-epiphyte-seagrass decline model’, which provides an indirect mechanism for the effects of increased nutrients on seagrass. This model also supports previous correlative observations of seagrass loss at the Port Adelaide WWTP sludge outfall in offshore Holdfast Bay, the Bolivar WWTP outfall north of Outer Harbour, and the Glenelg WWTP outfall in nearshore Holdfast Bay (Collings *et al.* 2006a).

While experimental results indicate that ammonium is directly toxic to both *Posidonia* and *Amphibolis*, the levels tested would only ever be experienced directly adjacent to effluent point discharges; levels of ammonium well away from discharge points are far lower (Collings *et al.* 2006a). Furthermore, while mesocosm experiments were only conducted over short time periods and a toxic response may take longer to occur, results from a field experiment did not indicate a direct toxic response to elevated nutrients over a 12-month period (Collings *et al.* 2006a). Thus, it is unlikely that broad-scale seagrass losses were due to a direct toxic effect from elevated nutrients.

Multiple stressors
For the reasons outlined above, it is possible that a combination of increased nutrients and increased turbidity from stormwater and wastewater triggered the initial seaward regression of nearshore seagrasses in Holdfast Bay.

Management implications arising from results of Task EP 1

- Nutrient levels along Adelaide’s coastline are clearly elevated due to wastewater, industrial, and stormwater discharges. Furthermore, experimental results from Task EP 1 unambiguously demonstrated that chronic, yet minor, increases in water column nutrients can cause the slow decline of *Amphibolis* and *Posidonia* in shallow, oligotrophic coastal waters. These results have clear implications for coastal managers with respect to the discharge of nutrients, not only into Adelaide’s coastal waters, but also to other shallow coastal waters where seagrasses occur. In the case of Adelaide, it is apparent that nutrients are being delivered from a number of wastewater treatment plants, specific industrial sources such as Penrice, and stormwater drains.

- Light conditions in the nearshore of Holdfast Bay are severely lowered by stormwater discharges. Work within Task EP 1 has shown that the lowered and variable light conditions in Holdfast Bay could be detrimental to seagrasses. These results have clear implications for coastal managers with respect to the discharge of stormwater. Overall, in terms of stormwater, it is not the freshwater *per se* that is damaging, but rather the optical properties of the water (suspended solids, dissolved organic material) and the nutrients carried by the water. Toxicants in stormwater do not appear to be a major issue for seagrass health off Adelaide.
- The meadow-forming seagrasses, *Amphibolis* and *Posidonia*, are important components of the nutrient cycling process off Adelaide. Therefore, historical and ongoing losses of these seagrasses have important ramifications for the ability of the system to assimilate land-based discharges of nutrients. This has implications for coastal managers in terms of attempts to halt seagrass declines and to commence seagrass rehabilitation.

Nominated actions arising from results of Task EP 1

Arising from the Task EP 1 series of technical reports are the following nominated actions:

- Reduce nutrient loads entering Adelaide's coastal waters in order for the system to have any chance of returning to its natural oligotrophic state.
- Reduce turbid and coloured stormwater inputs to Holdfast Bay in order to improve underwater light conditions.
- Undertake detailed mapping of *Amphibolis* distribution across the Adelaide metropolitan area, determine the lower depth limit of seagrasses in Holdfast Bay, and map seagrasses in the southern metropolitan area between Seacliff and Sellicks Beach.
- Conduct further research on the basic biology of *Amphibolis*, which appears to be a crucial, yet sensitive, component of nearshore seagrass systems in Gulf St Vincent.
- Conduct further field research on the effects of increased nutrients in different locations/depths and in conjunction with decreased light (a proxy for increased turbidity).
- Conduct research on rates of meadow expansion and recolonisation in denuded and fragmented areas.
- Conduct research on sediment re-suspension and impacts on seagrass health.
- Conduct further research to develop nutrient budgets, determine denitrification processes, and develop a nutrient mass-balance model of Gulf St Vincent.
- Evaluate and commence long-term monitoring of seagrass quality (or 'health') at sites adjacent to land-based discharges and at suitable control sites.
- Evaluate and commence long-term monitoring of the outer depth margin of *Posidonia* meadows in Holdfast Bay.
- Evaluate and commence long-term monitoring of seagrass meadow fragmentation at a range of sites in Holdfast Bay.
- Conduct a spatially intensive nitrogen stable isotope survey to determine the offshore and northern extents of nitrogen influence from WWTP and industrial outfalls along the Adelaide metropolitan coastline, and also characterise nitrogen stable isotope signatures of potential nitrogen sources.
- Conduct research on the photosynthetic parameters required for input to light-productivity models of *Amphibolis* and *Posidonia* off the coast of Adelaide.

1. Introduction

1.1. Background

1.1.1. Seagrass loss off Adelaide

Since the 1940s, over 5000 ha of seagrasses have been lost from the Adelaide metropolitan coast (Westphalen *et al.* 2004). In particular, major losses of the nearshore meadow forming seagrasses, *Amphibolis* and *Posidonia*, have occurred in Holdfast Bay with a gradual offshore regression of the ‘blue-line.’ The loss of these seagrasses is of major concern due to their importance for near-shore productivity, seabed stability, and biodiversity. Nonetheless, the primary cause(s) of nearshore seagrass decline in Holdfast Bay are poorly understood, partly because initial losses occurred from the shallow inshore margin advancing seaward; a situation in reverse to many losses reported in other regions of Australia and the world where poor water quality and reduced light conditions cause seagrasses to disappear from deep waters first.

Prior to European settlement, there were very few coastal inputs to Holdfast Bay. While the Patawalonga Creek and the Port River may have historically delivered some freshwater to the coast, engineering works and urbanisation during the 20th century substantially increased coastal inputs (Wilkinson 2005, Wilkinson *et al.* 2003, 2005a,b). Major changes included the diversion of the Torrens River away from inland wetlands directly to the ocean at West Beach, the commencement of industrial discharges into the Port River system (Wilkinson *et al.* 2005b), and the construction of numerous stormwater drains and several wastewater treatment plant (WWTP) outfalls (Wilkinson *et al.* 2005a). The historical condition of Holdfast Bay was probably once similar to the present status of most other coastal parts of Gulf St Vincent, i.e. relatively clear water with low levels of both nutrients and toxicants (Bryars *et al.* 2006). However, due to the various coastal inputs, Holdfast Bay is no longer pristine, with elevated levels of nutrients, toxicants, and turbidity being detected and reported regularly over the last 30 years (Bryars *et al.* 2006). Consequently, each of these potential stressors has been implicated in the historical loss of seagrasses (Westphalen *et al.* 2004). In addition, it is possible that reduced salinity associated with the freshwater coastal inputs also contributed to seagrass loss.

1.1.2. Task EP 1 of the Adelaide Coastal Waters Study

The Adelaide Coastal Waters Study (ACWS) is a major, multi-institutional study aimed at developing knowledge and tools to enable the sustainable management of Adelaide’s coastal waters by identifying causes of ecosystem modifications and the actions required to halt and reverse the degradation. The ACWS region extends from Port Gawler in the north to Sellicks Beach in the south (Fig. 1.1), but does not specifically include the Port River/Barker Inlet system.

The ACWS comprises six separate, but linked, research tasks. In an attempt to better understand causal mechanisms of seagrass loss, Task EP 1 “Assessment of the effects of inputs to the Adelaide coastal waters on seagrass ecosystems and key biota” was developed with four key objectives:

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3. To determine effects of nutrients on seagrasses
4. To determine effects of other stressors on seagrasses.

In order to address the four objectives of Task EP 1, a series of desktop, laboratory and field activities was undertaken between 2003-2006, with the results detailed in six technical reports:

- Westphalen *et al.* (2004) A review of seagrass loss on the Adelaide metropolitan coastline. ACWS Technical Report No. 2.
- Westphalen *et al.* (2005) Responses to reduced salinities of the meadow-forming seagrasses *Amphibolis* and *Posidonia* from the Adelaide metropolitan coast. ACWS Technical Report No. 9.
- Collings *et al.* (2006a) Elevated nutrient responses of the meadow-forming seagrasses *Amphibolis* and *Posidonia* from the Adelaide metropolitan coast. ACWS Technical Report No. 11.
- Collings *et al.* (2006b) Turbidity and reduced light responses of the meadow-forming seagrasses *Amphibolis* and *Posidonia* from the Adelaide metropolitan coast. ACWS Technical Report No. 12.
- Nayar *et al.* (2006) Nutrient fluxes in the meadow-forming seagrasses *Amphibolis* and *Posidonia* from the Adelaide metropolitan coast. ACWS Technical Report No. 13.
- Bryars *et al.* (2006) Field surveys 2003-2005: Assessment of the quality of Adelaide's coastal waters, sediments and seagrasses. ACWS Technical Report No. 14.

The present report summarises the outcomes of the six Task EP 1 technical reports as they pertain to the four key objectives outlined above. If readers require further information, they are directed to the individual technical reports. The present report also provides conclusions (in conjunction with relevant outcomes of technical reports from other ACWS Tasks) regarding the effects on *Amphibolis* and *Posidonia* of four key stressors that were identified in the first of the Task EP 1 technical reports (see Westphalen *et al.* 2004) as being potential causes of broad-scale seagrass loss along the Adelaide coastline, viz.:

- Toxicants
- Salinity
- Turbidity
- Nutrients

As requested by the project managers, Sections 7 and 8 detail information on Management Implications and Nominated Actions. The final section of the present report also lists the ACWS Stakeholder Issues and associated responses relevant to Task EP 1.

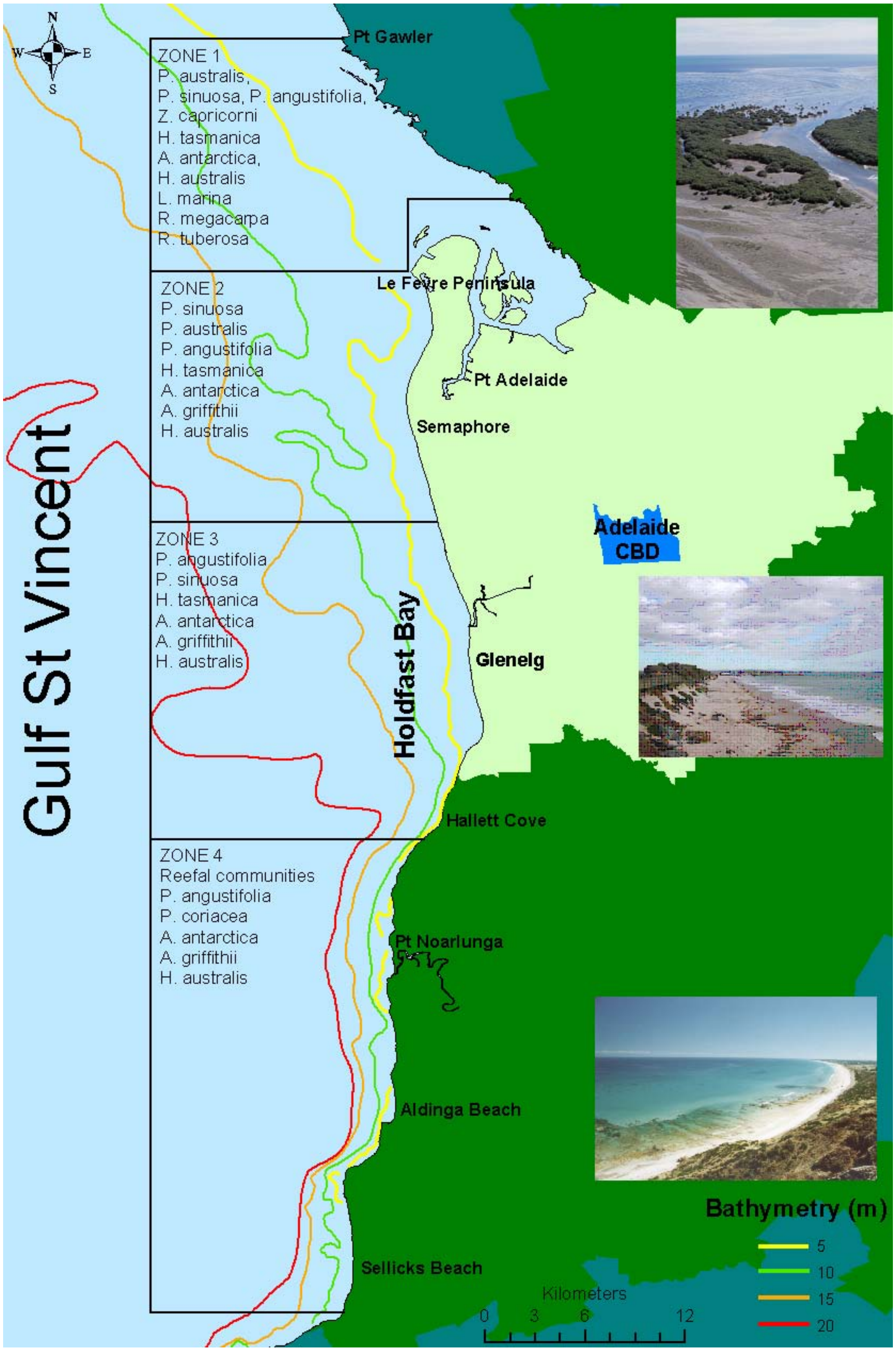

Figure 1.1 Map of the Adelaide metropolitan coastline showing the northern and southern boundaries of the Adelaide Coastal Waters Study region and Zones 1-4 used for field surveys in Task EP 1 (figure taken from Westphalen *et al.* 2004). Depth contour lines represent 5 m (yellow), 10 m (green), 15 m (orange) and 20 m (red). Full species names are listed in Table 1 of Westphalen *et al.* 2004. Shaded areas on land roughly indicate the level of urbanisation with very blue for the central business district (CBD), pale green for inner suburbs, darker green for outer suburbs and the city fringe (darkest).

2. Current Coastal Water, Sediment and Seagrass Quality

2.1 Background

Adelaide's coastal ecosystems have changed drastically over the past 60-70 years. At least 5000 ha of seagrass meadows (principally *Amphibolis* and *Posidonia*) have been lost and replaced mainly by bare sand habitat. Major areas of change are in the nearshore between Port Gawler and Outer Harbour, and in large parts of Holdfast Bay. In particular, major losses of seagrasses have occurred in nearshore Holdfast Bay. Due to the various coastal inputs operating since the 1930s, Adelaide's coastal waters are no longer pristine, with elevated levels of nutrients, toxicants, and turbidity regularly being reported over the last 30 years in both coastal inputs and coastal waters (Bryars *et al.* 2006). Historical data show that nearshore (< 5 m depth) waters in Holdfast Bay have consistently had elevated levels of nutrients since at least the 1970s and must be considered as eutrophic in the context of an oligotrophic system (Bryars *et al.* 2006). Significantly, the area of most pronounced elevation of nutrients between Glenelg and Grange coincides with the area of major nearshore seagrass losses in Holdfast Bay.

As part of Task EP 1, Bryars *et al.* (2006) conducted a number of field surveys during 2003-2005 to assess the quality of Adelaide's coastal waters, sediments, and seagrasses. Four zones were defined along the open coast to provide a spatial context for the field surveys (Figure 1.1; see Westphalen *et al.* 2004 for further details). This section of the present report provides a summary of the Bryars *et al.* (2006) report.

2.2 Aims

Specific objectives of the water quality surveys were to determine:

- Ambient offshore water quality within Zones 1-4 (Figure 1.1).
- Extremes of water quality within Zones 2 and 3 associated with major rainfall events.
- The spatial influence of nutrients derived from wastewater treatment plants and industrial discharges in Gulf St Vincent.

Water quality parameters considered useful for investigations included nutrients, chlorophyll-*a*, faecal coliforms, *Escherichia coli*, dissolved organic carbon, and several potential toxicants: organochlorine and organophosphate pesticides, triazine herbicides, and the herbicide Glyphosate (see Westphalen *et al.* 2004, for review of potential effects of these stressors on seagrasses). A large-scale survey was also conducted using the isotopic signature of seagrasses to determine the spatial extent of nitrogen derived from WWTPs and other sources in Gulf St Vincent. Neither turbidity nor light attenuation were measured during the surveys, as a series of light loggers were deployed to continuously measure underwater light intensity over a 12-month period as part of Task EP 1 (see Section 5 of the present report and Collings *et al.* 2006b). Salinity was also not measured because reliable data were available from historical sources and Task PPM1 of the ACWS.

Specific objectives of the sediment quality surveys were to determine:

- Ambient levels of sediment quality across Zones 1-4.
- Extreme levels of sediment quality associated with major stormwater discharges in Zone 3.

Potential toxicants considered useful for investigation included organochlorine and organophosphate pesticides, triazine herbicides, the herbicide Glyphosate, polyaromatic hydrocarbons, total petroleum hydrocarbons, and heavy metals (see Westphalen *et al.* 2004 for review of potential effects of these stressors on seagrasses).

Specific objectives of the seagrass quality surveys were to determine:

- The typical composition of existing seagrass meadows across Zones 1-4.
- The morphological characteristics of existing meadows in Zones 1-4.
- The outer depth limit of *Posidonia* meadows in Zones 2 and 3.
- The cover and taxonomic composition of epiphytes on existing meadows.

It must be noted that the emphasis of work by Bryars *et al.* (2006) was on the dominant subtidal genera of *Amphibolis* and *Posidonia*. However, some work was undertaken on *Heterozostera* in the intertidal region of Zone 1. Assessments were also deliberately conducted in areas away from obvious land-based discharges in order to provide an indication of seagrass quality representative of the whole Adelaide metropolitan coastline.

2.3 Outcomes

Water quality

- Water quality monitoring over existing offshore (5 and 10 m depths) seagrasses in the ACWS region between 2003-2004 showed no indication of elevated nutrient concentrations. However, results from a stable nitrogen isotope survey of offshore seagrasses indicate that the entire coast between Port Gawler and Port Noarlunga is being influenced by nitrogen from wastewater treatment plant (WWTP) and industrial outfalls (Figure 2.1). This outcome clearly demonstrates the inadequacies of solely monitoring dissolved nutrients in an oligotrophic system such as the offshore ACWS region.
- Water quality monitoring after three significant rainfall events during 2004-2005 indicated that major stormwater flows have a minor but localised influence on ambient nutrient levels in Holdfast Bay. In contrast, tests for other potential toxicants during these rainfall surveys detected only one compound (simazine) at a very low concentration out of a large suite of herbicides and pesticides. These results are in general agreement with results of previous studies.

Sediment quality

- Sediment quality analyses found very low or undetectable levels of toxicants in marine sediment samples collected adjacent to major stormwater outlets where they would most likely occur, and at offshore sites where terrestrially-derived sediments may be transported.
- No evidence was found to suggest that sediment quality is degraded due to toxicants.

Seagrass quality

- Historical records show that *Amphibolis* and *Posidonia* originally dominated Holdfast Bay and the nearshore region between Port Gawler and Outer Harbour. Since the 1940s, major losses of these meadows have occurred in several discrete locations.
- *Posidonia* is now the dominant seagrass across the ACWS area.
- *Amphibolis* is abundant only in the nearshore area from Semaphore to Henley Beach and Brighton to Marino. *Amphibolis* appears to have disappeared from much of the nearshore area between Port Gawler and Semaphore, and the area between Henley Beach and Brighton.
- The dominant species of *Posidonia* changes from *P.sinuosa* through *P. angustifolia* to *P. coriacea* going from north to south in depths of 5 and 10 m across the ACWS region. The lower depth limit (~15-18 m) of *Posidonia* in Holdfast Bay does not appear to have changed over the past 40 years.
- Aboveground biomass of representative offshore (5 & 10 m depths) *Posidonia* meadows generally appears normal (although meadows directly adjacent to land-based discharges were not surveyed). However, cover of seagrass meadows is fragmented in the nearshore and offshore southern parts of Holdfast Bay, indicating a disturbed system.

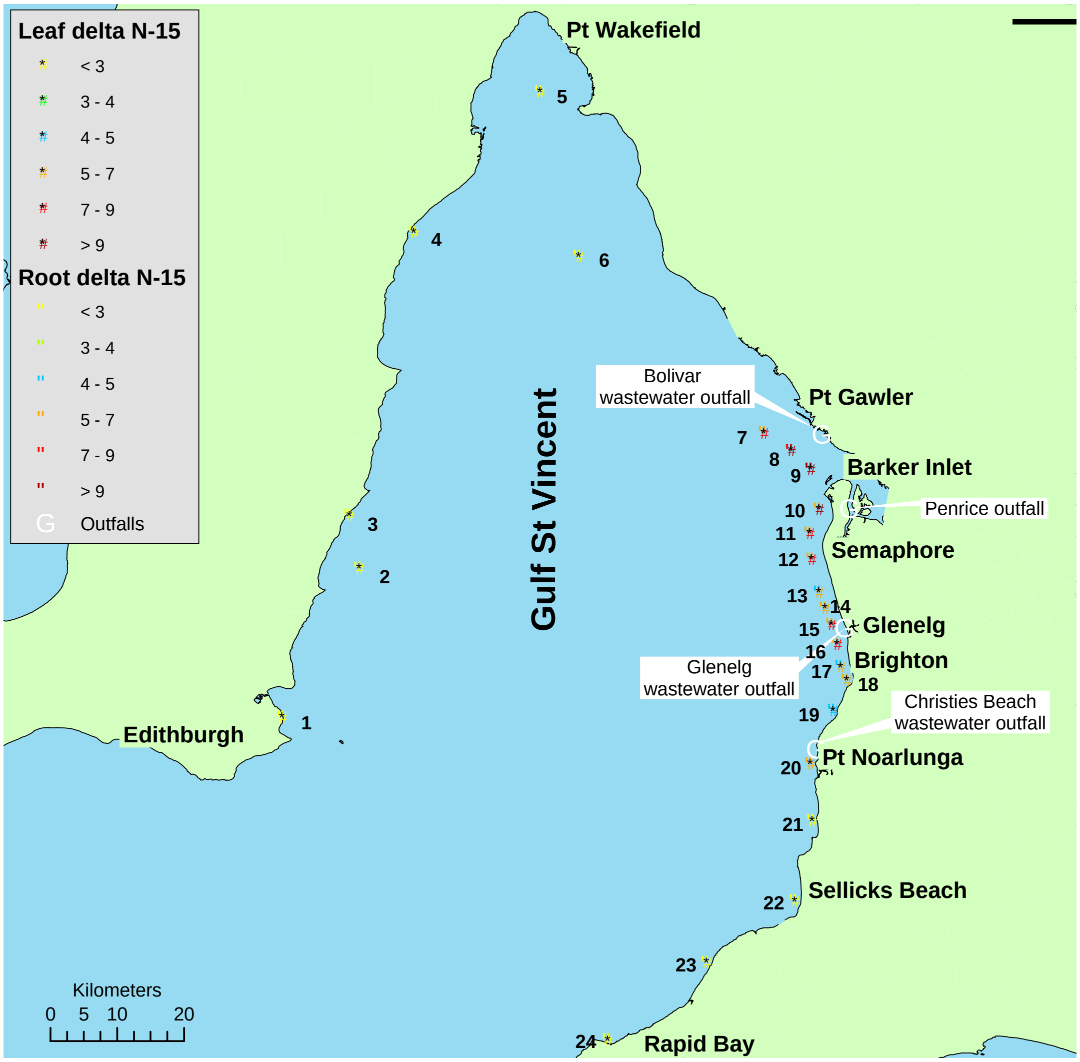

Figure 2.1 Spatial distribution of δ^{15}N in seagrass leaf and root samples collected from 24 sites around Gulf St Vincent (figure taken from Bryars *et al.* 2006). Note the elevated levels of δ^{15}N between Port Gawler and Port Noarlunga that are associated with nitrogen discharges from the Bolivar, Glenelg and Christies Beach wastewater treatment plants and the Penrice soda factory.

3. Nutrient Fluxes in Seagrasses

3.1 Background

While nutrient dynamics, uptake and resource allocation are well documented in tropical seagrass systems, there is a greater need for its understanding in temperate oligotrophic systems. This need becomes more critical as there is little information on the assimilative capabilities of seagrasses found in these regions, where a comparatively small increase in nutrient loads, particularly nitrogen, has a greater influence on the health of seagrasses than those found in mesotrophic systems. In the case of Adelaide, where losses of vast areas of seagrasses have been correlated with nutrient inputs, it is clear that we need to better understand the relationships between the input of nutrients and the uptake of various components of the ecosystem. Based on the detailed literature review of Westphalen *et al.* (2004), a conceptual model describing the fate of nutrients in Adelaide's coastal waters was constructed by Nayar *et al.* (2006). From the viewpoint of Task EP 1, however, the model was further simplified to show only the significant pathways (Figure 3.1). This section of the present report provides a summary of the Nayar *et al.* (2006) report.

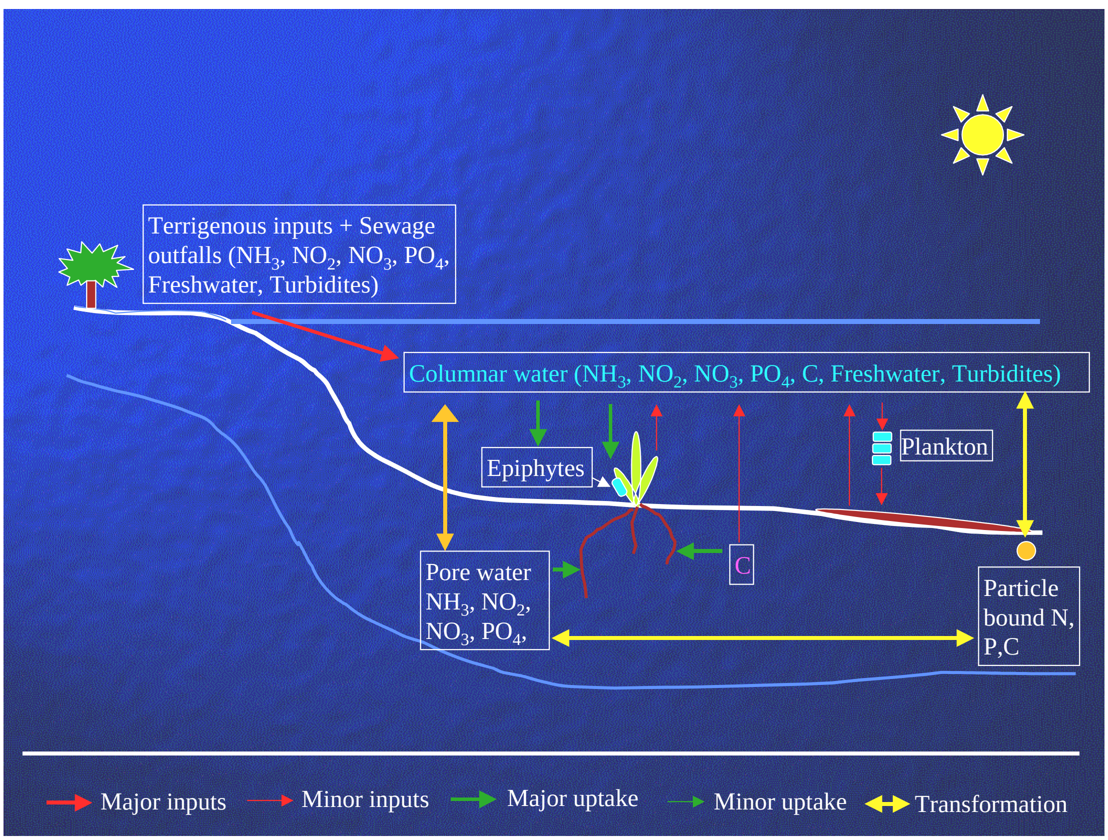

Figure 3.1 A simplified conceptual model used in Task EP 1 to show the fate of nutrients in Adelaide's coastal waters (figure taken from Nayar *et al.* 2006).

3.2 Aims

The work of Nayar *et al.* (2006) represents an attempt to quantify some of the important uptake rates of the biotic components of the system (Figure 3.1) and, through a modeling approach, place these rates in the broader context of the whole region and its nutrient inputs. Nayar *et al.* (2006) quantified the compartments in the modified model using uptake and resource allocation experiments that focused on the seasonal fluxes and resource allocation of carbon and nitrogen in *Amphibolis antarctica* and *Posidonia angustifolia*, both species commonly found off the Adelaide metropolitan coastline. The experiments involved isolating the seagrass in chambers and incubating them with a known concentration of nitrogen, phosphorus and / or carbon in the water column over time. Changes in the water column / pore water concentration of these nutrients over time were measured to determine fluxes. Uptake rates of the various compartments were measured to quantify resource allocation in *A. antarctica* and *P. angustifolia*.

3.3 Outcomes

Nitrogen uptake and resource allocation

The biomass standardised uptake rate of ammonium by plankton was higher than that of other biotic components (seagrass leaf, seagrass root, attached epiphytes). It peaked in winter (0.98 mg $N.g^{-1}$ $DW.h^{-1}$) in the plankton community associated with the *Posidonia* beds. Leaves, roots and epiphytes registered significantly higher uptake rates of ammonium in the *Amphibolis* complex than *Posidonia*. Uptake of ammonium by *Amphibolis* leaves ranged from 0.08 mg $N.g^{-1}$ $DW.h^{-1}$ (winter and spring) to 0.14 mg $N.g^{-1}$ $DW.h^{-1}$ (summer) and *Posidonia* leaves from 0.03 mg $N.g^{-1}$ $DW.h^{-1}$ (summer) to 0.08 mg $N.g^{-1}$ $DW.h^{-1}$ (spring). Overall, root uptake rates were lower than other biotic components. Epiphytes on *Amphibolis* had higher uptake rates than those on *Posidonia*. The effect of season was not significant for leaves, roots and epiphytes of *Amphibolis* and *Posidonia*. However, plankton uptake showed an effect of season because of the extremely high uptake rate in winter that was not evident at other times of the year.

In contrast to the general trend in ammonium uptake, nitrate uptake rates for biotic components were significantly affected by seasons. Among the various biotic components, plankton accounted for the highest nitrate uptake rates ranging from 0.003 mg $N.g^{-1}$ $DW.h^{-1}$ in summer (*Amphibolis* bed) to 0.69 mg $N.g^{-1}$ $DW.h^{-1}$ in winter (*Posidonia* bed). Nitrate uptake rates of leaves were relatively low and were greatest in spring at 0.009 and 0.011 mg $N.g^{-1}$ $DW.h^{-1}$ for *Posidonia* and *Amphibolis* respectively. Uptake of nitrate by the root component was negligible and did not differ with species or season The biotic uptake rates for nitrate were an order of magnitude lower than ammonium. It is evident that there was a clear affinity for ammonium over nitrate as a preferred inorganic nitrogen source by the two seagrass complexes (seagrass leaves, seagrass roots, epiphytes).

Nitrogen model

Using a modelling approach, uptake rates were scaled to the level of the Adelaide coast by taking into consideration the biomass-specific uptake rates and multiplying them by the estimated biomass of each of the components. This allowed a comparison of the annual input with the annual uptake rates of the different components. Uptake was far greater prior to 1978 due to a larger biomass of seagrass, and the greater ambient concentrations (which cause more rapid uptake) than is the case today. In 2005, estimates of ammonium uptake by the seagrass complex in the Adelaide region (seagrass and associated epiphytes) represent 465 tonnes of ammonium per year and 3.04 tonnes of nitrate. This accounts for 31% of the ammonium and less than 1% of the nitrate which is currently estimated to be discharged into Adelaide's waters. Of the ammonium and nitrate taken up by the biotic components, 99% and 88% respectively were accounted for by the seagrass and its associated epiphytes. Thus, whilst the model has demonstrated that the seagrass complex is responsible for a significant portion of the uptake, there are clearly other important sinks and processes which remain unaccounted for. The role of loss processes from the seagrass also requires quantification.

Of the total ammonium assimilated by biotic components, the seagrass complex accounts for nearly 90% of the total in winter and 100% in spring and summer. Assimilation by plankton accounted for the remaining 10% in winter, when higher plankton biomass is found in these waters. Currently, *Posidonia* seagrass complex accounts for most of the ammonium assimilated for all seasons in the study area. *Amphibolis* cover is less than 0.01% of the total seagrass cover in the ACWS study area (Blackburn and Dekker, 2005), making contribution by the *Amphibolis* complex to the assimilation of ammonium insignificant. Highest assimilation of ammonium was modeled in spring (2.3 t day^{-1}), followed by winter and summer (both 0.8 t day^{-1}).

In 2005, the total inputs of ammonium to the Adelaide coastal waters were reported to be 1509.3 t y^{-1} (Wilkinson *et al.* 2005b). The biotic uptake was just a third of the total inputs. Seagrass complex still accounted for 98% of the total biological assimilation from the metropolitan coastline. A summary of the fate of the anthropogenic inputs of ammonium and annual biotic assimilation rates is highlighted in Figure 3.2.

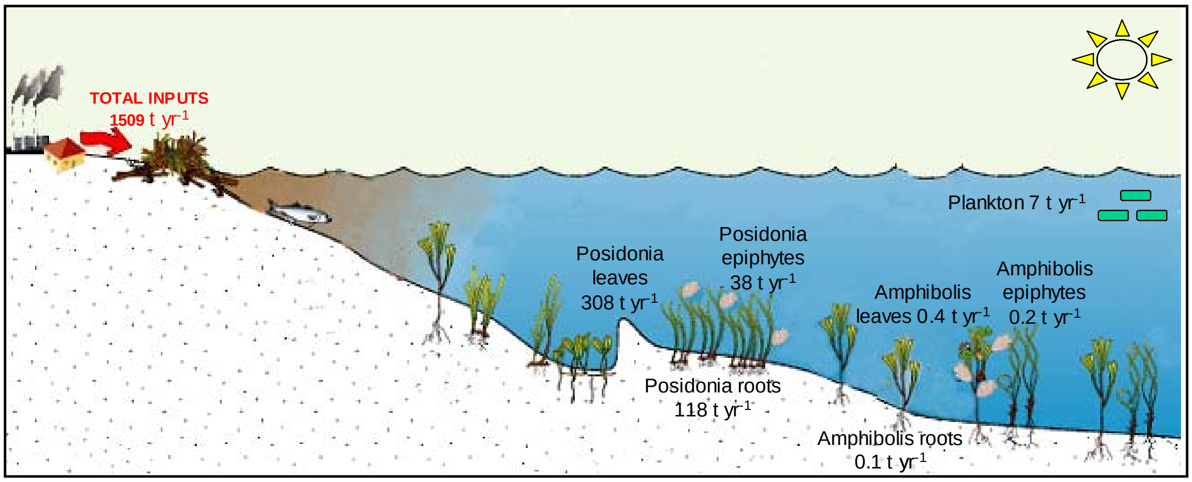

Figure 3.2. A simplified summary of the current annual ammonium biotic assimilation capacity in relation to the total anthropogenic inputs for the Adelaide coastal waters (figure taken from Nayar *et al.* 2006). Values in tonnes of ammonium year^{-1}.

A seasonal difference in biotic nitrate assimilation was evident, with highest assimilation rates in spring, followed by winter and least in summer. Plankton accounted for nearly 50% of the total biotic assimilation of nitrate in winter, with the seagrass complex assimilating most of the nitrate in spring and summer. As with ammonium assimilation, only the *Posidonia* seagrass complex took up a significant amount of nitrate, with leaves accounting for the bulk of the assimilation, followed by roots. Epiphytic assimilation was significant in spring and summer.

It is worth noting here that the current annual biotic nitrate assimilation of 3.44 t y^{-1} accounts for less than 1% of the total nitrate input of 473.6 t y^{-1} to the coastal waters off Adelaide. Of the total nitrate assimilated, the seagrass complex accounted for nearly 88% of the nitrate assimilated. A summarised version of the biotic assimilation capacity in the Adelaide metropolitan coast is highlighted in Figure 3.3.

The nitrogen model clearly indicates that the seagrasses on the coast of Adelaide represent an important component in the nitrogen cycle of the region. Given its importance, not only to nitrogen cycling, but also the stability of the ecosystem, further loss of these beds is likely to have important ramifications. To some degree, the model suggests that a decrease in seagrass biomass may result in elevated nutrient levels. Whilst this may, in turn, increase uptake rates, the indications are that this would be outweighed by a continuing loss of seagrass caused by the effects of eutrophication (see Section 4 of present report).

A critical appraisal of the model indicates that input levels are still in excess of the apparent ability of the biotic component to take up ammonium and nitrate. This is despite the fact that ambient levels are considerably reduced compared with historical levels. Clearly, there are sinks for nitrogen that have not yet been accounted for, viz. pore water, columnar water, sand, benthic microalgae, herbivores, etc. Quantifying these is an important future direction for this work. Another important advance for our understanding of nutrient cycling in this system is to go beyond uptake rates and quantify turnover rates of nutrients within each of the components.

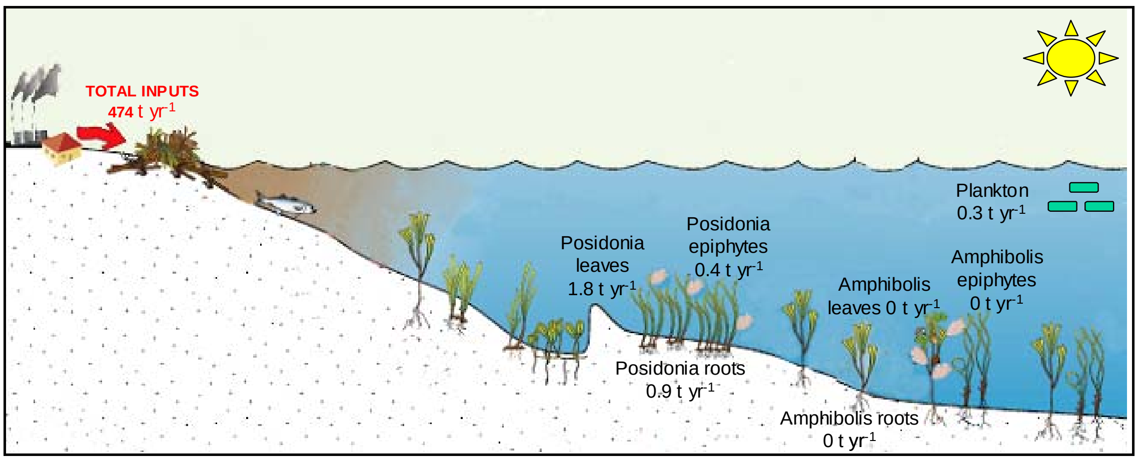

Figure 3.3. A simplified summary of the current annual nitrate biotic assimilation capacity in relation to the total anthropogenic inputs for Adelaide's coastal waters (figure taken from Nayar *et al.* 2006). Values in tonnes of nitrate year^{-1}.

Carbon uptake and resource allocation

Uptake of carbon by the seagrass complex was affected by both season and species. Carbon uptake rates of plankton were generally higher than other components of the system. Uptake rates ranged from 0.01 mg C. g^{-1} DW.h^{-1} (summer) to 0.61 mg C. g^{-1} DW.h^{-1} (spring) in *Posidonia* and 0.02 mg C. g^{-1} DW.h^{-1} (summer) to 0.93 mg C. g^{-1} DW.h^{-1} (winter) in *Amphibolis*. Carbon uptake by the *Amphibolis* complex was higher than the *Posidonia* complex. The *Amphibolis* complex had higher uptake rates in summer and the *Posidonia* complex was higher in spring.

Carbon is an essential structural component of photosynthetic organisms such as macrophytes and microphytes. Carbon uptake studies are often used as a good measure of the physiological state of these organisms. Water temperature and underwater irradiance are known to play a critical role in regulating seagrass productivity (especially leaf biomass), metabolism and carbon uptake. Fine sediments, probably from the Outer Harbour dredging operations, is likely to have resulted in lower carbon uptake and a reduction in the above-ground and below-ground biomass observed in summer. Shaded conditions from suspended particulates in the water column, coupled with high epiphytic load and sediment deposition on leaves in summer, may be responsible for reduced carbon uptake by seagrass leaves, thereby limiting seagrass growth. A combination of some of these factors might be responsible for the significant reduction in leaf (*Posidonia* and *Amphibolis*) and root biomass (*Amphibolis*) at the study site in summer. Whilst epiphytes may compete with seagrass for "resources", especially in *Amphibolis* where epiphytic loading is usually high, it is apparent from this study that inorganic carbon is not a limiting nutrient, thereby excluding the possibility of competition for this resource.

Phosphorus uptake

Total uptake of spiked inorganic phosphorus by biological components was negligible and never exceeded 0.5% of the total resource. Phosphorus uptake rate was affected by season with relatively higher rates in winter (0.05 mg PO_4. g^{-1} DW. h^{-1}) and least in spring (0.02 mg PO_4. g^{-1} DW. h^{-1}) for *Amphibolis* and highest in winter (0.07 mg PO_4. g^{-1} DW. h^{-1}) and least in spring (0.004 mg PO_4. g^{-1} DW. h^{-1}) for *Posidonia*.

Lower biological uptake rates of inorganic phosphorus could be attributed to carbonate sediments and particulates in the water column binding inorganic phosphorus, thus limiting its availability for biological uptake. Uptake rates were highest in winter and lowest in spring. As with carbon, smothering of the seagrass complex by suspended sediments probably resulted in reduced uptake during summer, as the chamber deployments during that season coincided with the dredging operations.

4. Effects of Nutrients on Seagrasses

4.1 Background

Adelaide's coastal waters were probably once oligotrophic, but since at least the 1970s, elevated levels of water column nutrients have occurred in Holdfast Bay and at several localised areas associated with wastewater outfalls (Bryars *et al.* 2006). For example, background levels for ammoniacal nitrogen, oxidised nitrogen, and free reactive phosphorus at a shallow site in western Gulf St Vincent were 0.008, 0.011, and 0.001 mg L^{-1}, respectively (Collings *et al.* 2006a), while the long-term (10-year) mean values of ammoniacal nitrogen, oxidised nitrogen, and total phosphorus taken from the Grange, Henley Beach, and Glenelg jetties in the area where nearshore losses have occurred were 0.042, 0.034, and 0.044 mg L^{-1}, respectively (data calculated from Gaylard 2004). Peak values associated with WWTP outfalls are far greater: directly in the Port Adelaide WWTP sludge outfall discharge, ammoniacal nitrogen = 0.59 mg L^{-1}, phosphorus = 0.127 mg L^{-1}; while directly in the Glenelg WWTP outfall, ammoniacal nitrogen = 3.15 mg L^{-1}, phosphorus = 1.19 mg L^{-1}, and oxidised nitrogen = 1.48 mg L^{-1} (see Bryars *et al.* 2006 for review of previous studies). Furthermore, stable isotope work has shown the spatial extent of influence from anthropogenically-derived nitrogen (see Section 2). Clearly then, nutrient levels have historically been elevated along the Adelaide metropolitan coast, and experimental investigation of the effects of elevated nutrients on *Amphibolis* and *Posidonia* was needed. This section of the present report provides a summary of the Collings *et al.* (2006a) report that investigated the effects of elevated nutrients on *Amphibolis* and *Posidonia*.

4.2 Aims

Experimental investigations were conducted on two fronts:
(1) Acute exposure experiments in mesocosms, and
(2) A chronic exposure experiment in the field

Specifically, Collings *et al.* (2006a) addressed five questions:

a) Do elevated levels of nutrients cause a physiological stress response (in terms of chlorophyll fluorescence measurements)?
b) Do increased levels of nutrients affect growth of the seagrasses?
c) Can small increases in nutrient levels, over long (annual) periods, cause seagrass decline?
d) If decline occurs, is it associated with increased epiphyte loading?
e) Are the findings consistent between *Amphibolis antarctica* and *Posidonia sinuosa*?

4.3 Outcomes

Acute exposure
Three experiments were conducted by Collings *et al.* (2006a) in controlled conditions in outdoor tanks using various levels of nutrients for differing exposure times:
Experiment 1: 20 mg L^{-1} ammonium for 72 hr
Experiment 2: 2.5 and 10 mg L^{-1} ammonium, 1 mg L^{-1} phosphorus for 72 hr, and
Experiment 3: 5 mg L^{-1} ammonium + 1 mg L^{-1} phosphorus for 4 weeks at different light intensities and on epiphytised and non-epiphytised plants.
In each experiment, the photosynthetic response of *Amphibolis* and *Posidonia* was monitored using a Diving PAM (see Collings *et al.* 2006a).

Increased levels of nutrients were seen to have an acute effect on the quantum yield of *Amphibolis antarctica* and *Posidonia sinuosa*. *Amphibolis* appears to be more susceptible to the effects of nutrients than *Posidonia* for any given increase in nutrients. Extremely high levels (20 mg L^{-1} of ammonium and 5 mg L^{-1} of phosphorus) caused a rapid decrease in effective quantum yield of both species, but more so in *Amphibolis* (Figure 4.1). At slightly more moderate levels of 10 mg L^{-1} of ammonium and 1 mg L^{-1} of phosphorus in Experiment 2, both nutrients caused decreases in effective quantum yield in an additive, rather than a multiplicative manner. Again, at these levels, *Amphibolis* fared worse than *Posidonia*. Over a longer timescale of 4 weeks in Experiment 3, an increase in nutrients of 5 mg L^{-1} of ammonium and 1 mg L^{-1} of phosphate caused a decrease in maximum quantum yield of *Amphibolis* that was not mirrored in *Posidonia*. There was a strong indication of an interactive effect of light climate on this nutrient effect, whereby nutrient damage was observed only in higher light environments (reflecting those found at 3 and 7 m). However, this was not statistically significant.

Mesocosm experiments are constrained by the fact that they represent an artificial environment that, over time, will alter and become very different to the natural system they are supposed to mimic. For this reason, experiments in these systems are necessarily relatively short term. This makes it difficult to demonstrate chronic effects, and it is unlikely that any response to slightly raised nutrients will result in significant effects on plants within the timeframe allowed. For this reason Experiments 1-3 deliberately targeted acute high intensity effects of nutrients, as an adjunct to the longer-term field study which utilised far lesser increases in nutrients (see below).

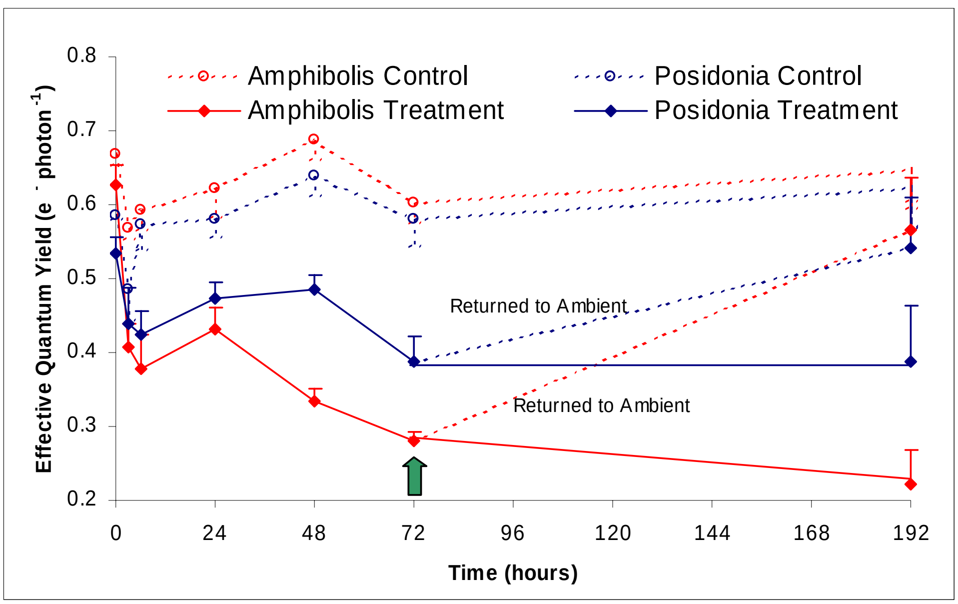

Figure 4.1 Photosynthetic response (effective quantum yield) of *Amphibolis antarctica* and *Posidonia sinuosa* exposed to 20 mg L^{-1} of ammonium for a 72 hour period in Experiment 1 (figure taken from Collings *et al.* 2006a). Epiphytised and non-epiphytised plants have been pooled. After 72 hours, three of the treatment (T) replicates were returned to ambient conditions equivalent to those of the controls (C), whilst the remaining two remained under high nutrient conditions. This is indicated on the graph by the solid control lines splitting into a dashed (ambient) line and a solid line representing the average of those replicates with continuing high nutrients.

Chronic exposure

Two meadow-forming seagrasses, *Amphibolis antarctica* and *Posidonia sinuosa*, were exposed to minor increases (2-6 x) of water column nutrients (ammoniacal nitrogen, oxidised nitrogen, free reactive phosphorus) using slow-release fertiliser over a 12-month period at a shallow (~2 m depth), oligotrophic marine site in Gulf St Vincent, South Australia. The addition of fertiliser had a major detrimental effect on the aboveground biomass of both seagrass species over the course of the experiment (Figure 4.2). Biomass declines were characterised by reductions in plant density and leaf abundance in *A. antarctica*, and by reductions in leaf density and leaf length in *P. sinuosa* (Figure 4.3). Seagrass biomass declines were coincident with significant increases in epiphyte load in the fertiliser treatments of both species. No significant differences between control and fertiliser treatments were found for seagrass leaf initiation/elongation rates or seagrass photosynthetic yield, but gastropod density was higher in fertiliser treatments at the completion of the experiment. It is postulated that the declines we observed were directly related to increased epiphyte loads, thus providing rare empirical support for the widely accepted nutrient-epiphyte-seagrass decline model (Figure 4.4). While the precise mechanism of epiphyte-mediated seagrass loss is unclear, our results unambiguously demonstrate that chronic, yet minor, increases in water column nutrients can cause the slow decline of *Amphibolis* and *Posidonia* in shallow, oligotrophic coastal waters where anthropogenic inputs occur. Such a response had not been previously demonstrated through experimentation.

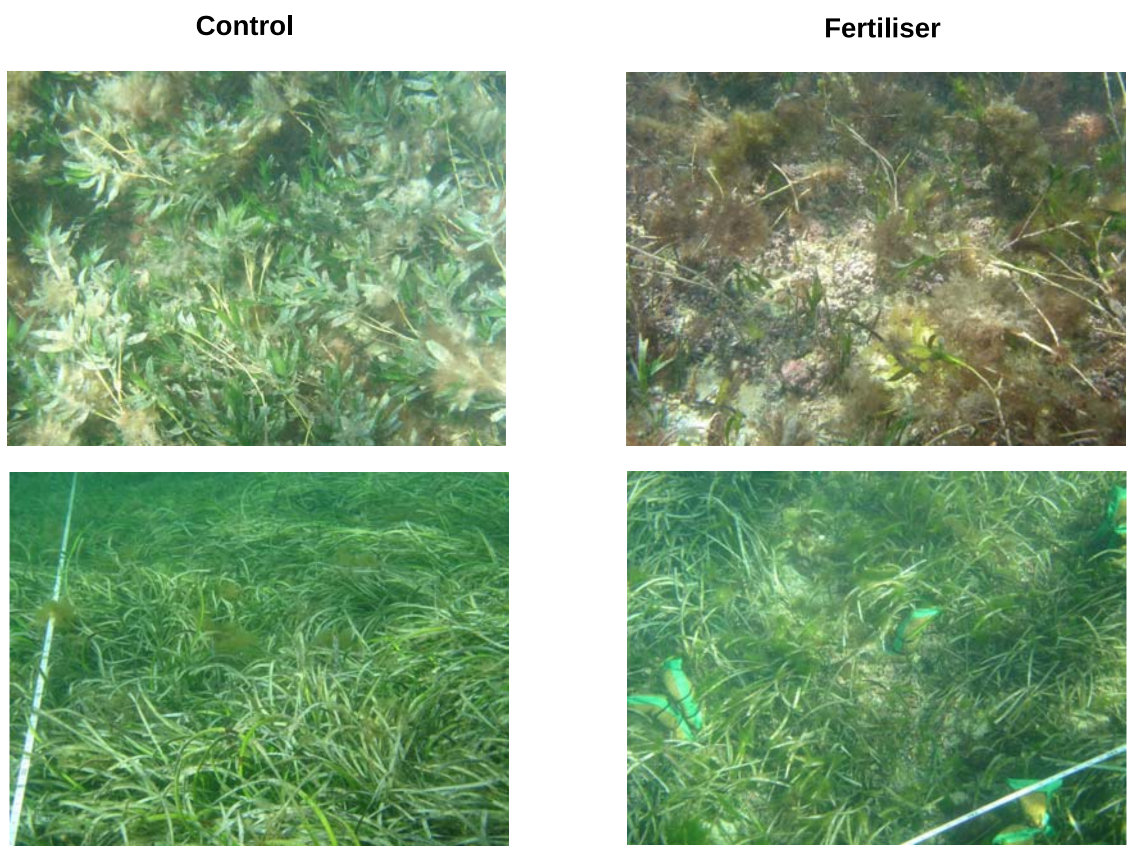

Figure 4.2 Differences between control (left) and fertiliser (right) treatments for *Amphibolis antarctica* (above) and *Posidonia sinuosa* (below) due to chronic exposure to elevated nutrient concentrations in the fertiliser treatments (pictures taken from Collings *et al.* 2006a). Fertiliser treatments had been exposed to elevated nutrients since March 2005, with the *Amphibolis* photos taken in January 2006 and the *Posidonia* photos taken in December 2005. Note the degraded nature of both seagrass species in the fertiliser treatments compared to the control treatments.

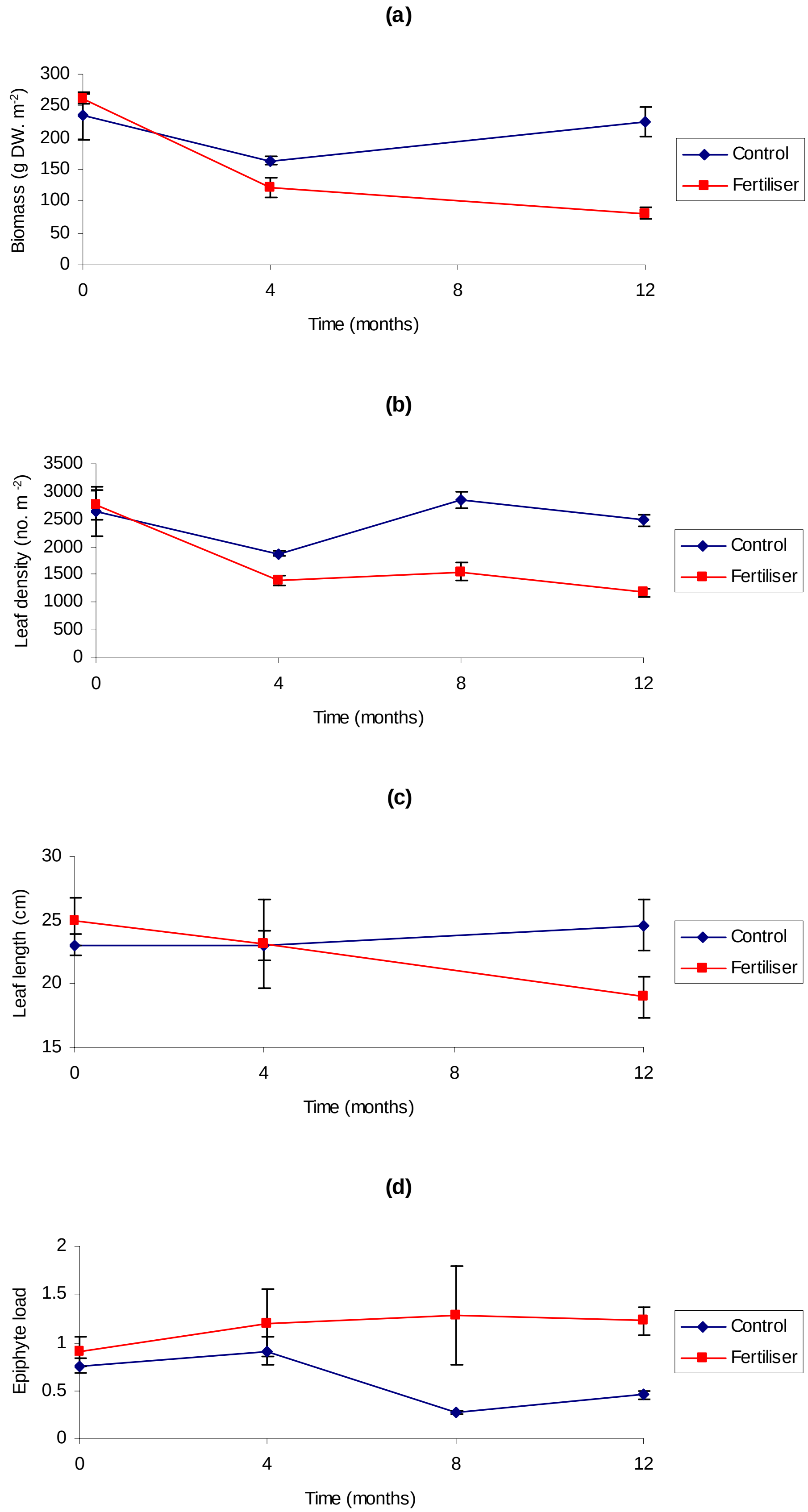

Figure 4.3. Mean (± SE, n = 3) values of (a) aboveground biomass, (b) leaf density, (c) leaf length, and (d) epiphyte load, for *Posidonia sinuosa* in control and fertiliser treatments across a 12-month experimental period (figure taken from Collings *et al.* 2006a). Note the declines in aboveground biomass, leaf density, and leaf length, but coincident increase in epiphyte load, of the fertiliser treatment.

Overall conclusions

In relation to the initial questions raised, the following conclusions can be made:

- Short-term exposure to high levels of ammonium and phosphate does result in changes in chlorophyll fluorescence, which is typically associated with the effects of stress.
- A significant change could not be demonstrated in either *Posidonia* leaf extension rates, or the initiation rate of new leaves within a head for *Amphibolis*. However, a reduction in the number of leaves per head, in both the field and mesocosm studies indicates that the leaf *loss* rate must be increased under conditions of high nutrients. Similarly, high nutrient conditions did not significantly affect *Posidonia* leaf extension rates. Thus the apparent decrease in length of leaves is likely due to an increased rate of erosion at the distal end of the leaf.
- Small experimental increases in nutrients (nitrogen, phosphorus) have unequivocally been shown to cause deleterious effects in seagrass beds. This is the most profound finding of Task EP 1. These effects include lower aboveground standing biomass, lower leaf/stem density, and a decreased size of individual plants or leaves. Whilst, in 12 months, we were unable to demonstrate complete disappearance of the seagrass bed, it is considered unlikely that the bed would have survived another year of eutrophication.
- We cannot definitively say that epiphyte loading was the cause of the decline in the field experiment, particularly as stress effects were evident in mesocosm experiments over a period too short to involve an effect of epiphytes. However, the clear demonstration of an associated increase in epiphytism under conditions of high nutrients, the maintenance of structural strength of *Posidonia* in raised nutrient conditions, and the literature demonstrating the likely effects of such high epiphyte levels provide a strong case for epiphyte–mediated seagrass decline.

In conclusion, we have clearly demonstrated that increased nutrients represent a serious stress to *Amphibolis* and *Posidonia*. In a long-term field setting we have shown a decline in aboveground biomass of both species in response to a chronic, yet minor, increase in water column nutrients in the field. Importantly, for the Adelaide situation, this decline has been demonstrated at nutrient levels well within the bounds of historical water quality records.
It is postulated that the declines we observed were directly related to increased epiphyte loads and/or changes in epiphyte composition, thus providing rare empirical support for the widely accepted nutrient-epiphyte-seagrass decline model. However, the hypothesis still requires manipulative experimental verification. Furthermore, observations from the present study are consistent with field observations associated with large-scale losses of *Amphibolis* and *Posidonia* in many locations across southern Australia where the nutrient-epiphyte-seagrass decline model has been used previously to explain the losses. However, short-term studies with high levels of nutrients also demonstrated signs of physiological stress with a low likelihood of any epiphyte-mediated effect.

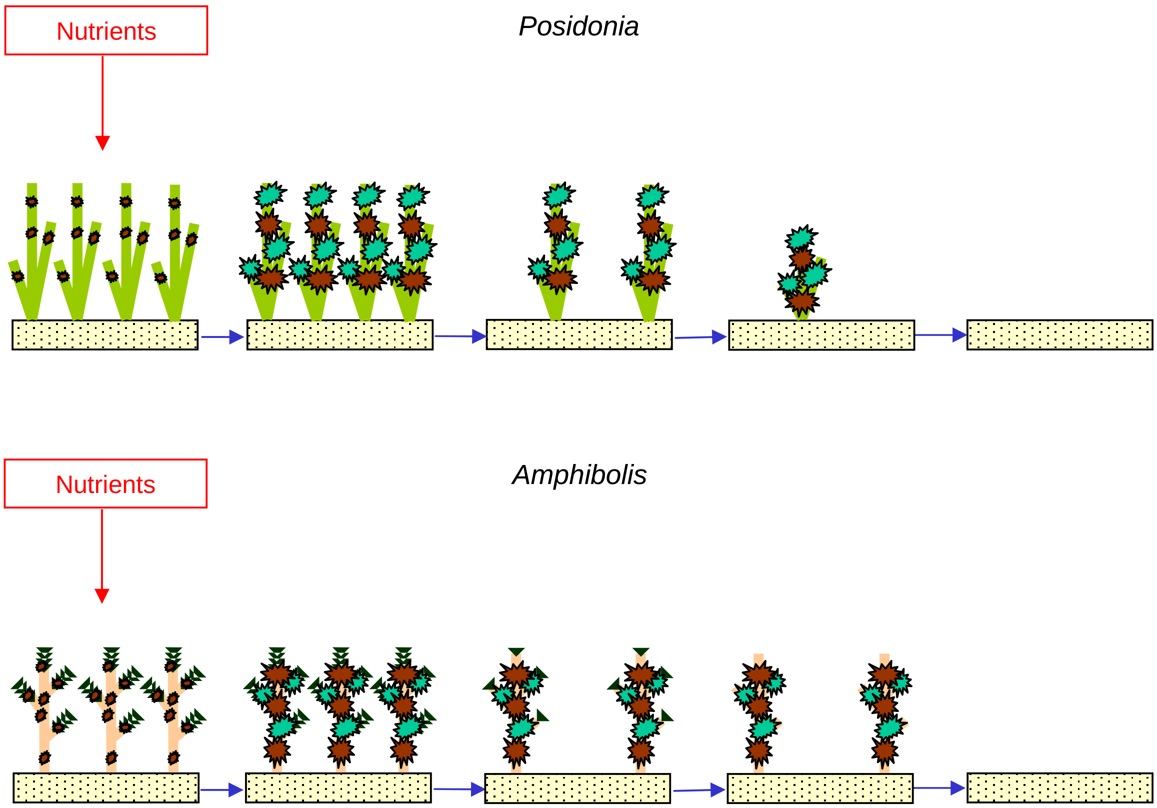

Figure 4.4. Schematic of the Nutrient-Epiphyte-Seagrass Decline Model in *Posidonia* (above) and *Amphibolis* (below), showing how an increase in water column nutrients can cause an increase in epiphytes, and inturn, a decline in leaf density and leaf length for *Posidonia* and a decline in stem density and leaf density for *Amphibolis*; eventually ending in complete seagrass loss for both species.

5. Effects of Other Stressors on Seagrasses

5.1. Salinity

Background

Prior to European settlement, there was very little freshwater input to Holdfast Bay. The Patawalonga Creek and the Port River may have delivered some freshwater to the coast but, due to engineering works and urbanisation, inputs increased substantially during the 20th century. Major changes included the diversion of the Torrens River away from inland wetlands directly to the ocean at West Beach, and the construction of numerous stormwater drains and wastewater outfalls (Westphalen *et al.* 2004). The Adelaide metropolitan coastline is currently affected by many different sources of freshwater. For Holdfast Bay, average annual freshwater input is currently estimated at 44.8 GL from the Torrens River, Patawalonga, and Holdfast Drains catchments collectively (Wilkinson *et al.* 2004) and 18.4 GL from the Glenelg wastewater treatment plant (WWTP) outfall (Wilkinson *et al.*2003). Importantly, discharges to the sea are relatively constant year-round from the Glenelg WWTP outfall, but are pulsed and mainly occur from May to October in the catchments (Wilkinson *et al.* 2004). As the timing of seagrass recession along the Adelaide coast within Holdfast Bay coincided with the completion of stormwater outlets in this region (Seddon 2002) and there is currently a significant annual input of freshwater (63.2 GL) to the region, it seems possible that decreases in nearshore salinity could be related to seagrass loss. Prior to the ACWS, very little experimental work had been done on the effects of reduced salinity on *Amphibolis* and *Posidonia* (Westphalen *et al.* 2004). Thus, further investigation was necessary. This section of the present report provides a summary of the Westphalen *et al.* (2005) report that investigated the effects of reduced salinity on *Amphibolis* and *Posidonia*.

Aims

Experimental investigation was undertaken by Westphalen *et al.* (2005) in three main parts relating to the lowered salinity tolerances of:

1. Adult plants of *Posidonia sinuosa* and *Amphibolis antarctica*
2. Seedlings of *A. antarctica*, and
3. Fruit and seedlings of *Posidonia angustifolia.*

Outcomes

The main outcomes of the experiments were that:

- Both *A. antarctica* and *P. sinuosa* adult plants are highly tolerant to short-term (72 hours) reductions in salinity.
- Major reductions in salinity for prolonged periods (weeks) are required to kill *A. antarctica* and *P. sinuosa* adult plants (see Figure 5.1)
- Short-term reductions in salinity can affect *A. antarctica* seedlings and *P. sinuosa* fruits (see Figure 5.2).

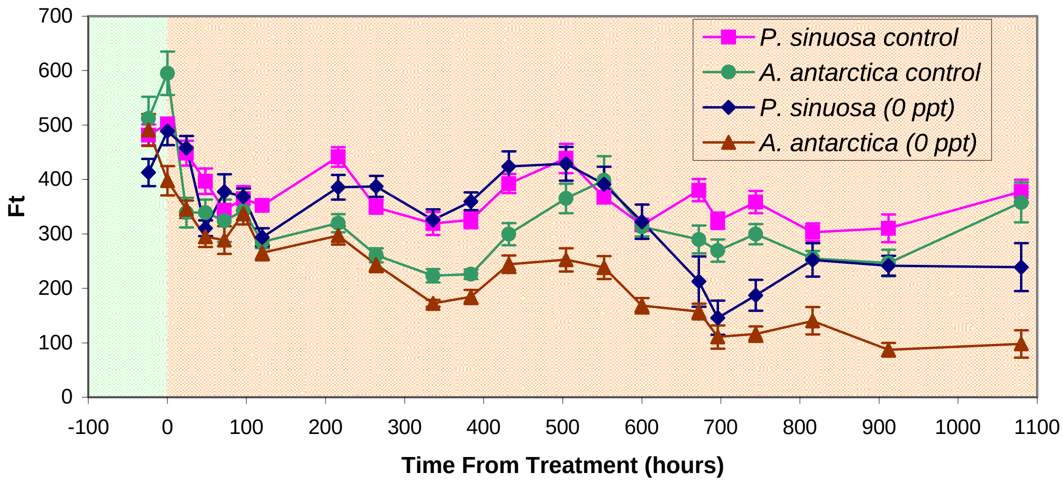

Figure 5.1. Average ambient fluorescence (Ft) of *A. antarctica* and *P. sinuosa* within each measurement time over a seven week experimental period showing the slow decline of the two seagrasses in complete freshwater (0 ppt) compared to those in seawater (control) (figure taken from Westphalen *et al.* 2005).

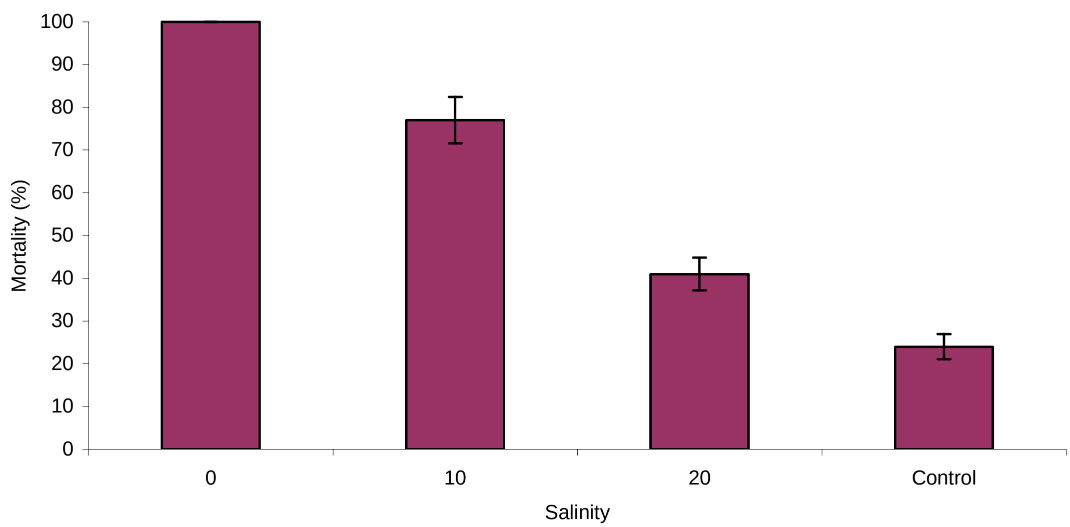

Figure 5.2. Mortality (expressed as a percentage) of *Posidonia angustifolia* fruits exposed for 72 hours at a range of salinities (figure taken from Westphalen *et al.* 2005). Error bars represent standard error, n=4. At 0 ppt salinity, all replicates exhibited 100% mortality and so no error bars are shown.

5.2. Light (turbidity/coloured dissolved organic matter)

Background

Since at least the 1930s, turbid and dark-coloured stormwater discharges have entered Holdfast Bay (Wilkinson *et al.* 2005a, Bryars *et al.* 2006, see Figure 5.3). Plumes from these discharges may persist for many days and have the potential to dramatically reduce light reaching seagrasses on the seabed, particularly in the nearshore region where broad-scale losses of seagrasses have occurred (Westphalen *et al.* 2004). It is well established that prolonged shading will eventually cause the decline of seagrasses. However, shading experiments need to be conducted over very long timescales (1-2 years), which were beyond the scope of Task EP 1. Furthermore, short-term laboratory or mesocosm experiments utilising other measures of seagrass performance are more suited to acute, rather than chronic, responses. Instead, a seagrass productivity model was created to determine the likely outcomes when utilising a 12-month data-set of *in situ* light measured at the seabed off Adelaide during 2005-2006 (see Collings *et al.* 2006b). This section of the present report provides a summary of the Collings *et al.* (2006b) report.

Aims

Collings *et al.* (2006b) aimed to test the general hypothesis that the light climate was worse in the nearshore zone at 3m depth (from where seagrass beds have been lost) than at other sites further from shore (6, 12, and 18m depth) where seagrass has not been lost. This was extended to include variability in the photokinetic parameters of the plants to investigate whether the light conditions could explain the loss of seagrass when depth-specific photokinetic parameters were utilised. There were five specific hypotheses to be tested:

1. That there was less photosynthetically active radiation (PAR) at the nearshore site than further offshore. This would represent strong evidence that the light climate may be responsible for productivity levels that were insufficient to support the seagrasses.

2. That the light climate was more variable at the nearshore site than further offshore. On the basis of the fact that plants are known to tune their photosynthetic apparatus (often slowly) to the ambient light conditions, large fluctuations in light may make this a difficult task.

3. That reduced light levels were caused by increased land-based runoff. Tests of this hypothesis investigate the likely cause of the light environment experienced by the Adelaide metropolitan coast.

4. That variability in light climate (without any change in mean levels) was disadvantageous for seagrasses on the basis of lower productivity. This puts Hypothesis 2 into the perspective of an effect on the plants. Whilst it does not answer the question whether these conditions caused seagrass loss, it does indicate whether variability is inherently disadvantageous to seagrasses by way of decreased productivity.

5. That the light climate of the Adelaide metropolitan coast produced conditions which, in the context of reasonable photokinetic parameters, explain the loss of seagrass from the nearshore zone of this region. Using modeling, Collings *et al.* (2006b) investigated whether a scenario could be produced which demonstrates poorer productivity for the nearshore 3m site (which has lost its seagrass beds) than it does for other sites further offshore, yet still allows for lower productivity at the deeper 18m edge (where productivity is marginal) than at the intermediate 6m and 12m sites (which support dense seagrass beds and are presumably relatively productive).

Figure 5.3. Major discharge of stormwater from the Torrens River into Adelaide's coastal waters on 25 October 2005. Photo: S. Bryars

Outcomes

With regard to each of the hypotheses, the following conclusions were drawn:

1. That there was less photosynthetically active radiation at the nearshore site than further offshore. Using an extensive data set that spanned the entire annual cycle, it was demonstrated conclusively that this hypothesis was false. In terms of the average daily dose of PAR, there was greater light at the nearshore site than at sites further offshore (Figure 5.4). Whilst the optical clarity of the water was significantly reduced in the region where seagrass had been lost (Figure 5.5), the effect of the shorter water column outweighed this, resulting in greater light at the 3m site than any other.

2. That the light climate was more variable at the nearshore site than further offshore. Despite the fact that variability can be described in various ways (e.g. range, standard deviation, standard deviation as a function of mean), all measures indicated a greater variability in the 3m site than at the others.

3. That reduced light levels were caused by increased land-based runoff.
Whilst this was not a hypothesis which could be tested by experimentation, there was a clear correlation between discharge volumes of the main land-based sources (which were treated as a surrogate for the total land-based discharges) and the optical clarity of the water (Figure 5.6). This relationship was evident across a medium timescale (i.e. comparison of months) and on a daily timescale. There was no consistent lag evident on a daily scale, indicating rapid mixing of the turbid water to quite some distance from shore. However, the effect was far more muted at sites further offshore, indicating some degree of entrainment and/or relatively rapid settlement of suspended particles from the water column.

4. That variability in light climate (without any change in mean levels) was disadvantageous for seagrasses on the basis of lower productivity.
Using our model with a variety of modeled light datasets, it was established that a constant daily light field resulted in greater productivity than a light field that represented the same total amount of light but was delivered in a more variable fashion (i.e. one dark day in five). Thus, in the absence of any difference in mean light levels, variability in light climate represents a stressor for the plants.

5. That the light climate of the Adelaide metropolitan coast produced conditions which, in the context of reasonable photokinetic parameters, explain the loss of seagrass from the nearshore zone of this region.
There was variable support for this hypothesis, depending on the set of photokinetic parameters utilised. Unless depth-dependent changes in photokinetic parameters were utilised, it was not possible to demonstrate, for either *Posidonia* or *Amphibolis*, a scenario consistent with the productivity-induced loss from the nearshore site whilst seagrass beds were maintained further offshore. When depth-dependent changes in photokinetic parameters were included, it was possible to demonstrate a scenario whereby seagrass may have been lost because of poor productivity levels. However, confidence in the extrapolation of results from Western Australia is not high, because it would indicate that *Posidonia sinuosa* makes a nett productivity loss on an annual cycle at all sites, and therefore should not occur at any depth, which it quite clearly does. Thus, whilst it is possible to demonstrate a situation for *Amphibolis* that shows seagrass loss on the basis of poor productivity (Figure 5.7), the conclusion must be that the model fails to rule out the possibility, but further work is required to provide strong support. What can be said, however, is that nearshore Adelaide coastal waters represent a poor environment in terms of optical quality, and that these conditions, whilst they may not be solely responsible for seagrass loss in the area, represent a significant stressor, which may, in conjunction with another factor, be responsible for such a loss.

This work has yielded an excellent record of the light climate of the Adelaide coast in the Grange region. In order to strengthen arguments for the effect of this light environment on the loss of seagrass beds, further work should be directed towards identifying the photosynthetic parameters of *Posidonia* and *Amphibolis* off the coast of Adelaide. The application of such parameters from Western Australia has proven a useful exercise, but to take this model further requires a knowledge of the characteristics of local populations, both across an annual cycle and as they vary across a depth / light profile.

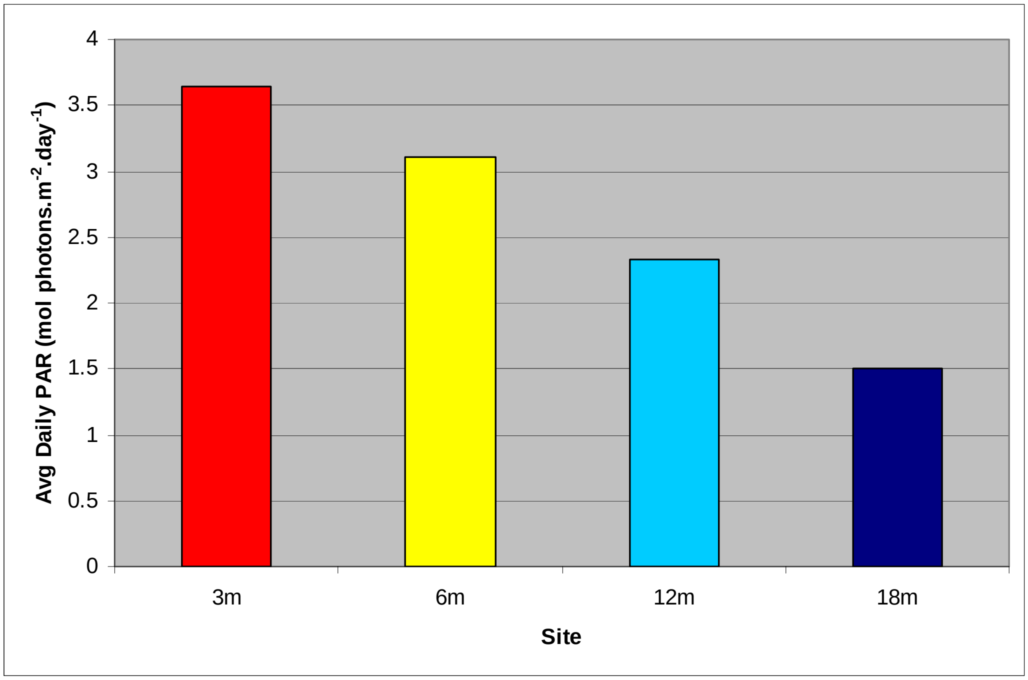

Figure 5.4 Daily photosynthetically active radiation averaged across the annual cycle at 4 depths off Grange. Note that the average daily insolation, calculated across the entire year is greatest at the shallowest depth, and decreases as depth increases (figure taken from Collings *et al.* 2006b). Error bars are not provided as this variability is addressed directly elsewhere (see Collings *et al.* 2006b).

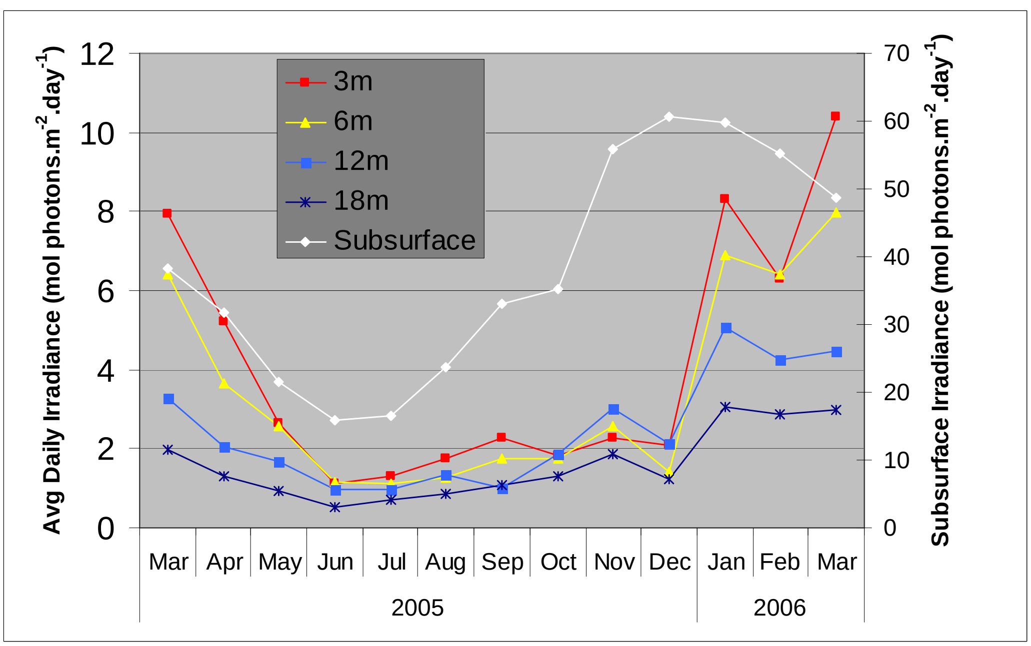

Figure 5.5 Average daily photosynthetically active radiation for each month at each of the sampling locations (figure taken from Collings *et al.* 2006b). Subsurface light is presented on the right hand axis. Whilst the 3 m and 6 m sites were lighter than the deeper sites in the period January to May, over the period June to December, light in the shallower regions was depressed to a similar level as that found at 18 m.

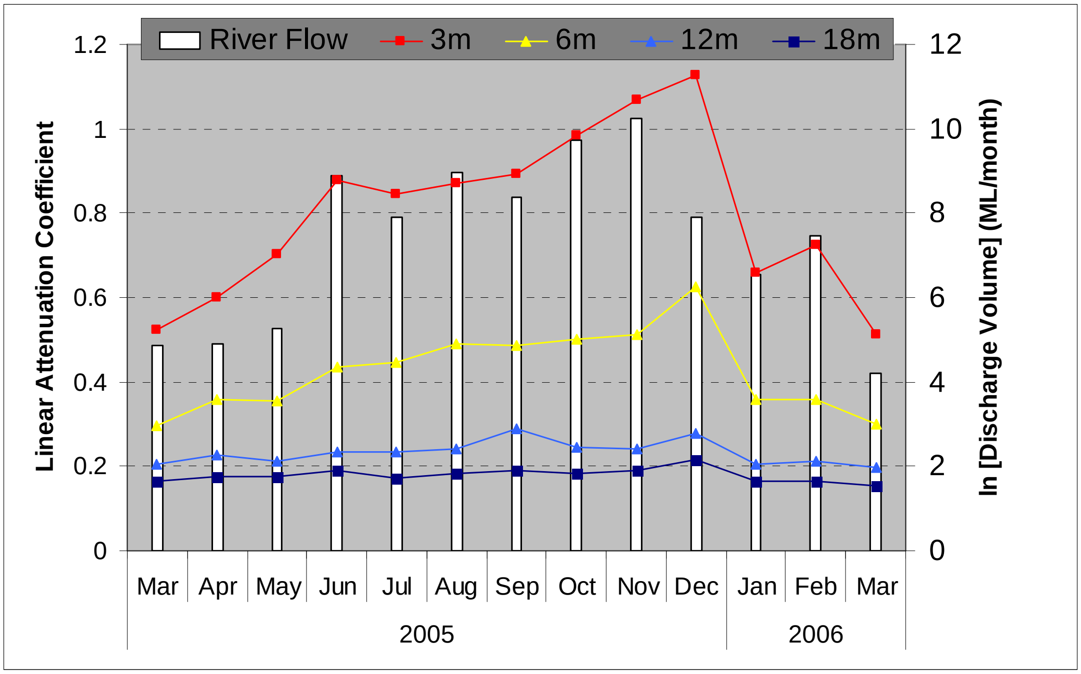

Figure 5.6 Average linear attenuation coefficients calculated for each month at each site with the combined Barcoo Outlet and Torrens River outflows overlaid (figure taken from Collings *et al.* 2006b). River flow is expressed on a natural log scale. The river flow value for March 2006 is based upon a scaled up estimate of flow from the small dataset available, rather than a full month. The apparent response of attenuation to river flow is most notable in the nearshore (3 m) region and becomes more muted at sites further from the shore.

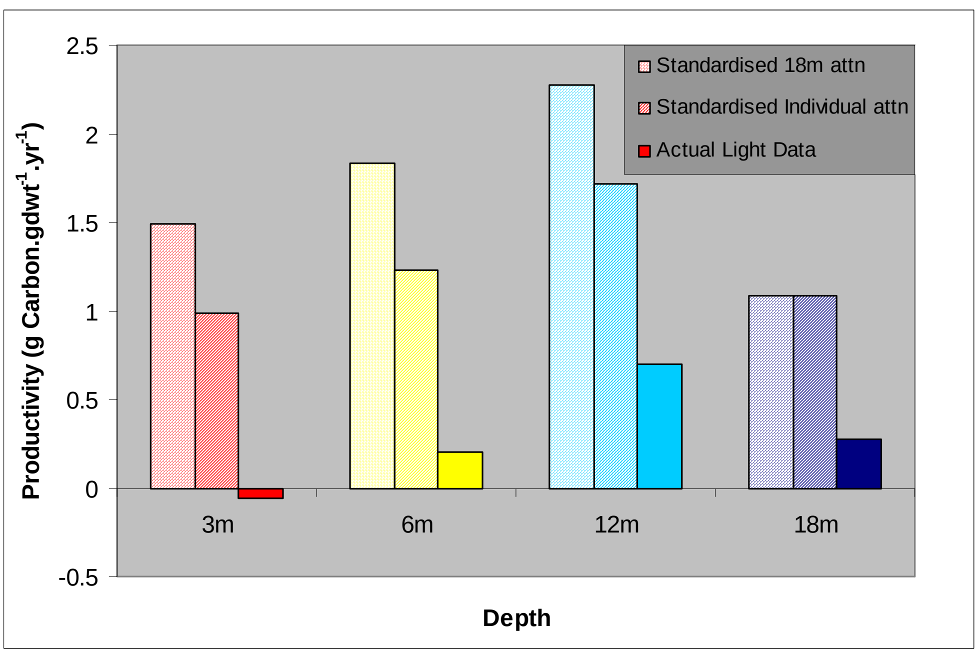

Figure 5.7 Annual *Amphibolis* productivity assuming maintenance of constant I_K, P_{max} and Rd values across time but allowing for changes across the depth profile (figure taken from Collings *et al.* 2006b). Details are provided in Table 1 of Collings *et al.* (2006b). The model is run the standardised light field assuming 18 m attenuation (brickwork), with the standardised field using measured attenuation (striped), and with the actual light data (solid bars). The 3 m site is less productive than either the 6 or the 12 m sites, under all conditions, and is worse than the 18 m site under all light scenarios except for that which assumed a constant light attenuation coefficient across sites.

5.3. Toxicants

The effect of toxicants on seagrasses was not experimentally tested in Task EP 1. Rather, evidence from the published literature (Westphalen *et al.* 2004), combined with data on toxicant concentrations in stormwater (Wilkinson *et al.* 2005a, Bryars *et al.* 2006) and coastal waters and sediments (Bryars *et al.* 2006) were used to draw conclusions about toxicants being a possible cause of large-scale seagrass losses off Adelaide (see Section 6). The review by Westphalen *et al.* (2004) highlighted that various potential toxicant stressors exist, including heavy metals, herbicides, and petrochemicals. However, Westphalen *et al.* (2004) did not consider that experimental investigation of any of these compounds was warranted, given the existence of other more likely stressors such as reduced salinity, increased turbidity, and elevated nutrients.

5.4. Multiple stressors

Most of the experimental/modelling work conducted within Task EP 1 focused on the effects of single factors on seagrass health. However, due to the mix of potential stressors associated with wastewater and stormwater entering Adelaide's coastal waters, it has been postulated that a combination of factors may have caused historical seagrass losses (see Westphalen *et al.* 2004). Thus, Experiment 3 of the mesocosm studies (see Section 4 of the present report), was designed to simultaneously test the effects of elevated nutrients, reduced light, and increased epiphyte load, on *Amphibolis antarctica* and *Posidonia sinuosa*. Whilst Experiment 3 suggested an interesting interaction between ammonium concentration and light level, any extrapolation of results to the field was hampered by the unrealistically high nutrient concentrations and the short time frame (4 weeks) used. In light of the results of the chronic nutrient exposure field experiment (Section 4), it would be pertinent to conduct a similar experiment using light level (via *in situ* shading) as a crossed-factor. Such an experiment may well provide further valuable information about the relative importance of nutrients versus turbidity for seagrass survival off Adelaide's coastline.

6. Conclusions

The following four sections summarise the outcomes of the 6 Task EP 1 technical reports and provide conclusions (in conjunction with relevant outcomes of technical reports from other ACWS tasks) regarding the effects of the four potential stressors of toxicants, salinity, turbidity, and nutrients on *Amphibolis* and *Posidonia* loss along the Adelaide metropolitan coastline.

6.1. Toxicants

Toxicants were unlikely to have been responsible for broad-scale historical seagrass losses because:

- Toxicants have only been sporadically detected in very low concentrations in freshwater entering Adelaide's coastal waters (Wilkinson *et al.* 2005a, Bryars *et al.* 2006).
- Concentrations required to affect seagrass physiological processes are relatively high (Westphalen *et al.* 2004), and due to rapid dilution in the marine environment (see Pattiaratchi *et al.* 2006), the historical levels detected in stormwater could never have reached levels capable of having an impact.
- Bryars *et al.* (2006) found all toxicants to be undetectable in the coastal waters off Adelaide following peak stormwater flows when detection would be most likely.
- Bryars *et al.* (2006) found very low or undetectable levels of potential toxicants in marine sediment samples collected adjacent to major stormwater outlets where they are most likely to occur, and at offshore sites where terrestrially derived sediments may potentially be transported.

6.2. Salinity

Reduced salinity from stormwater and wastewater was unlikely to have been responsible for broad-scale historical seagrass losses because:

- Both *Amphibolis antarctica* and *Posidonia sinuosa* adult plants are highly tolerant to short-term (72 hours) reductions in salinity (Westphalen *et al.* 2005).
- Major reductions in salinity for prolonged periods (weeks) are required to kill adult *A. antarctica* and *P. sinuosa*.
- In the nearshore region where stormwater enters Adelaide's coastal waters and at locations adjacent to wastewater outfalls, reductions in salinity are only minor (Kaempf 2005, Bryars *et al.* 2006, Pattiaratchi *et al.* 2006)

However, short-term reductions in salinity can affect *A. antarctica* seedlings and *P. sinuosa* fruits. Thus it is possible that stormwater and wastewater could influence recruitment processes on a very localised scale.

6.3. Turbidity

Increased turbidity from stormwater could have contributed to broad-scale historical losses of nearshore seagrass because:

- Since at least the 1930s, turbid stormwater discharges have entered Holdfast Bay (Wilkinson *et al.* 2005a, Bryars *et al.* 2006).
- Hydrodynamic modelling indicates that coastal inputs to Holdfast Bay tend to be entrained in the nearshore region (Pattiaratchi *et al.* 2006).
- A series of light loggers moored for 1-year during 2005-2006 in Holdfast Bay showed that during periods of stormwater flows, nearshore seabed light conditions were drastically reduced (Collings *et al.* 2006b).

- Physiological modelling using field data indicates that, under certain scenarios, light levels across the 12-month period were sufficiently low to cause the death of *Amphibolis* at 3m depth but not at deeper depths (Collings *et al.* 2006b). Furthermore, it is highly likely that nearshore light conditions were worse during the 1940s to 1960s (when much of the nearshore seagrass loss occurred, Westphalen *et al.* 2004), because discharges from the Torrens River were significantly greater than today (Wilkinson 2005).

While we cannot determine whether the light climate alone might have been the cause of the loss of inshore seagrass, the possibility cannot be discounted on the basis of the Task EP 1 work, and at the very least, the poor light climate in nearshore Holdfast Bay will provide an extra stress on the seagrass beds over and above any other stressors.

6.4. Nutrients

Increased nutrients from stormwater and wastewater could have been responsible for broad-scale historical seagrass losses because:

- Since at least the 1970s, elevated levels of water column nutrients have occurred in Holdfast Bay and at other localised areas associated with wastewater outfalls (Bryars *et al.* 2006). Unnatural nutrient inputs to Holdfast Bay would have commenced as early as the 1930s when the Torrens River was diverted to the sea, the Glenelg WWTP began operating (Wilkinson *et al.* 2003, 2005a), and the Penrice Soda factory began operating in the Port River (EPA 2006).
- Results of a nitrogen stable isotope survey clearly indicate that the existing offshore seagrasses from Port Gawler to Port Noarlunga do receive nitrogen sourced from WWTP and industrial outfalls, viz. Penrice, (Bryars *et al.* 2006) that have been operating for many decades (Wilkinson *et al.* 2003, Wilkinson *et al.* 2005b). Clearly then, nearshore seagrasses (prior to their loss) would also have been exposed to those same nutrient sources.
- Results of a major long-term field experiment unambiguously proved that chronic, yet minor increases in water column nutrients (as might be associated with WWTP inputs) could cause the slow decline of *Amphibolis* and *Posidonia* in shallow, previously nutrient-poor coastal waters (Collings *et al.* 2006a). These results support the ‘nutrient-epiphyte-seagrass decline model’, which provides an indirect mechanism for the effects of increased nutrients on seagrass. This model also supports previous correlative observations of seagrass loss at the Port Adelaide WWTP sludge outfall in offshore Holdfast Bay, the Bolivar WWTP outfall north of Outer Harbour, and the Glenelg WWTP outfall in nearshore Holdfast Bay (Collings *et al.* 2006a).

While experimental results indicate that ammonium is directly toxic to both *Posidonia* and *Amphibolis*, the levels tested would only ever be experienced directly adjacent to effluent point discharges; levels of ammonium well away from discharge points are far lower (Collings *et al.* 2006a). Furthermore, while mesocosm experiments were only conducted over short time periods and a toxic response may take longer to occur, results from a field experiment did not indicate a direct toxic response to elevated nutrients over a 12-month period (Collings *et al.* 2006a). Thus, it is unlikely that broad-scale seagrass losses were due to a direct toxic effect from elevated nutrients.

6.5. Multiple stressors

For the reasons outlined above, it is possible that a combination of increased nutrients and increased turbidity from stormwater and wastewater triggered the initial seaward regression of nearshore seagrasses in Holdfast Bay.

7. Management Implications

- Nutrient levels along Adelaide's coastline are clearly elevated due to wastewater, industrial, and stormwater discharges. Furthermore, experimental results from Task EP 1 unambiguously demonstrated that chronic, yet minor, increases in water column nutrients can cause the slow decline of *Amphibolis* and *Posidonia* in shallow, oligotrophic coastal waters. These results have clear implications for coastal managers with respect to the discharge of nutrients, not only into Adelaide's coastal waters, but also to other shallow coastal waters where seagrasses occur. In the case of Adelaide, it is apparent that nutrients are being delivered from a number of wastewater treatment plants, specific industrial sources such as Penrice, and stormwater drains.

- Light conditions in the nearshore of Holdfast Bay are severely lowered by stormwater discharges. Work within Task EP 1 has shown that the lowered and variable light conditions in Holdfast Bay could be detrimental to seagrasses. These results have clear implications for coastal managers with respect to the discharge of stormwater. Overall, in terms of stormwater, it is not the freshwater *per se* that is damaging, but rather the optical properties of the water (suspended solids, dissolved organic material) and the nutrients carried by the water. Toxicants in stormwater do not appear to be a major issue for seagrass health off Adelaide.

- The meadow-forming seagrasses, *Amphibolis* and *Posidonia*, are important components of the nutrient cycling process off Adelaide. Therefore, historical and ongoing losses of these seagrasses have important ramifications for the ability of the system to assimilate land-based discharges of nutrients. This has implications for coastal managers in terms of attempts to halt seagrass declines and to commence seagrass rehabilitation.

8. Nominated Actions

Arising from the Task EP 1 series of technical reports are the following nominated actions:

- Reduce nutrient loads entering Adelaide's coastal waters in order for the system to have any chance of returning to its natural oligotrophic state.
- Reduce turbid and coloured stormwater inputs to Holdfast Bay in order to improve underwater light conditions.
- Undertake detailed mapping of *Amphibolis* distribution across the Adelaide metropolitan area, determine the lower depth limit of seagrasses in Holdfast Bay, and map seagrasses in the southern metropolitan area between Seacliff and Sellicks Beach.
- Conduct further research on the basic biology of *Amphibolis*, which appears to be a crucial, yet sensitive, component of nearshore seagrass systems in Gulf St Vincent.
- Conduct further field research on the effects of increased nutrients in different locations/depths and in conjunction with decreased light (a proxy for increased turbidity).
- Conduct research on rates of meadow expansion and recolonisation in denuded and fragmented areas.
- Conduct research on sediment re-suspension and impacts on seagrass health.
- Conduct further research to develop nutrient budgets, determine denitrification processes, and develop a nutrient mass-balance model of Gulf St Vincent.
- Evaluate and commence long-term monitoring of seagrass quality (or 'health') at sites adjacent to land-based discharges and at suitable control sites.
- Evaluate and commence long-term monitoring of the outer depth margin of *Posidonia* meadows in Holdfast Bay.
- Evaluate and commence long-term monitoring of seagrass meadow fragmentation at a range of sites in Holdfast Bay.
- Conduct a spatially intensive nitrogen stable isotope survey to determine the offshore and northern extents of nitrogen influence from WWTP and industrial outfalls along the Adelaide metropolitan coastline, and also characterise nitrogen stable isotope signatures of potential nitrogen sources.
- Conduct research on the photosynthetic parameters required for input to light-productivity models of *Amphibolis* and *Posidonia* off the coast of Adelaide.

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10. Stakeholder Issues

ACWS Task EP 1 responses to ACWS Stakeholder Issues (July 2001)

3.2.1 Nutrients (in sediments / water column)

3.2.1.5 How important are any de-nitrifying processes in sediments along Adelaide's coastline in assimilating discharged nutrients?

We do not have estimates of denitrification rates *per se* for the sediments along the Adelaide metro coast. Our earlier studies with chambers suggested very low ambient concentrations of oxidised nitrogen (NO_x) in the columnar waters and pore waters ranging from less than 0.03 to 0.10 mg L^{-1}. This makes any long-term incubations with ambient levels of NO_x for denitrification studies difficult. All the spiked benthic chamber experiments involving $^{15}NO_3$ are too short term to obtain a reliable measure of denitrification rates.

While seagrass dominated sediments are conducive for high denitrification rates due to their anoxic nature and high organic matter loading, Welsh *et al.* (2000) reported values in an intertidal *Zostera noltii* meadow accounting for as little as 0.1% of total nitrate fluxes. Hemminga et al. (1991) estimated losses due to denitrification in the range of 0.1 to 2 g N m^{-2} yr^{-1}. Risgaard-Petersen and Ottosen (2002) also reported low denitrification rates in *Zostera marina* in a temperate system. Seagrasses have been reported to influence sediment denitrification in two ways (i) by stimulating coupled nitrification-denitrification by the oxygenation of the top layer of the sediments and by releasing dissolved organic carbon through the roots and by trapping particulate organic carbon by the above ground biomass, and (ii) by inhibiting denitrification by enhancing the competition for nitrogen between the roots and the nitrifying and denitrifying bacteria (Rysgaard et al., 1995; Risgaard-Petersen and Jensen, 1997; Welsh et al., 2000).

Since fluxes and denitrification rates reported by other researchers and the flux rates measured by us are extremely small in relation to other significant nitrogen fluxes in seagrass, ignoring their influence on the total nitrogen budget of the system could be reasonably justified.

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3.2.2 Pollutants (transport and fate of heavy metals, pesticides, ammonia)

3.2.2.1 Are there other parameters of concern in the coastal waters in addition to or instead of nutrients?

Yes. Suspended sediments and colour dissolved organic matter in stormwater contribute to the poor optical quality of coastal waters.

3.2.2.3 Is nitrogen/ammonia toxicity an issue for seagrass – is toxicity directly related to concentration?

Acute toxicity experiments conducted in controlled conditions in outdoor tanks showed that both *Posidonia* and *Amphibolis* are sensitive to elevated levels of dissolved ammonia (ammonium). At 20 mg L^{-1} ammonium, there was a major stress response from *Posidonia* and *Amphibolis*. While this response was rapidly reversed when plants were returned to normal concentrations after 72 hours exposure, plants remaining at the elevated ammonium levels continued to display the stress response. At concentrations of $\leq$ 10 mg L^{-1} ammonium, *Posidonia* and *Amphibolis* both showed a statistically significant (but small) response. In a multi-factor tank experiment, *Amphibolis* showed a significant (but small) response to 5 mg L^{-1} ammonium (plus 1 mg L^{-1} phosphorus). *Posidonia* showed no response in the equivalent treatment levels. It was apparent from all of the experimental work that *Amphibolis* is more sensitive than *Posidonia* to increased ammoniacal nitrogen.

While experimental results indicate that ammonium is directly toxic to both *Posidonia* and *Amphibolis*, the levels tested would only be experienced under real conditions directly adjacent effluent point discharges; levels of ammonium well away from discharge points are likely to be far lower. Furthermore, toxicity testing in tanks was done over a few weeks while toxic effects may only be apparent over a very long time period. Nonetheless, long-term exposure to even slightly raised levels of ammonium could be harmful to *Posidonia* and *Amphibolis* and cannot be discounted as a contributing factor to seagrass losses off Adelaide.

3.2.2.5 Are there any latent effects of DDT and other pesticide use on seagrass? (Biota likely to be better indicators than seagrass)

While there is little historical information available on levels of potential toxicants entering, or present in, Adelaide's coastal waters, all reported levels have been very low or below detectable limits. Recent sediment and water samples collected for Task EP 1 found no traces of DDT off Adelaide. Furthermore, the known levels of chemical exposure required to affect seagrass health are highly unlikely to occur off Adelaide's coastal waters due to rapid dilution. Even if harmful levels for seagrasses and associated biota did occur in land-based discharges, any effects would only be seen on a very localised scale around the point of discharge and could not explain the large-scale historical losses seen off Holdfast Bay during past decades.

3.2.4 Salinity – dispersion and interactions / impacts modelling

3.2.4.1 What is the impact of low salinity levels on seagrass communities (and different species within communities)?

Adult plants of *Amphibolis antarctica* and *Posidonia sinuosa* were considered in terms of their response to short (72 hours) and long-term (seven weeks) exposure to salinities as low as 0 ppt. Both *A. antarctica* and *P. sinuosa* were highly tolerant to short-term reductions in salinity. Only after seven weeks of exposure to salinities of ~ 1 ppt were the plants essentially killed. Observations of freshwater inputs along Adelaide's metropolitan coast suggest that the likelihood of occurrence of salinity levels less than 10 ppt in the vicinity of seagrass beds is low except close to sources. As a factor determining the large-scale loss of adult seagrasses, in particular *A. antarctica* and *P. sinuosa*, reduced salinity is unlikely.

The viviparous seedlings of *A. antarctica* and the fruits of *Posidonia angustifolia* were also considered in terms of their tolerance to reduced salinity. The floating seedlings and fruits of these species are the major transport mechanism outside established areas and more likely to be exposed to reduced salinities than the adults. Photosynthetic efficiency of *A. antarctica* seedlings was substantially reduced after short-term (72 hours) exposure to salinities below ~ 5 ppt. Although none of the test specimens was killed by the salinity dilution, it may well be expected that survival after more prolonged exposure would be limited. *Posidonia angustifolia* fruits suffered high levels of mortality when subjected to salinity levels of 10 ppt or less for a period of 72 hours.

The capacity for either *P. angustifolia* or *A. antarctica* to successfully recruit into areas of reduced salinity is probably minimal. Although the generality of these results to other species of either genus is unknown, the expansion of populations of either *Amphibolis* or *Posidonia* into new areas, which would be the primary role of propagules, will be determined at least in part by the salinity regime (amongst other factors such as depth, substrate, wave action, etc). It follows that, while freshwater may not have been a factor in historical large-scale seagrass losses, it may well play a role in determining the capacity for natural regeneration / recovery at sites close to terrigenous freshwater inputs.

3.2.4.2 What is the cumulative impact of the low salinity / high turbidity discharges from the various coastal stormwater outlets on seagrass health?

Stormwater is comprised of freshwater (i.e. low salinity water) and various suspended and dissolved compounds. Following heavy rains, turbid plumes of stormwater are regularly observed off Adelaide's coast. While lowered salinity is unlikely to have caused large-scale historical seagrass losses due to the tolerance of adult plants and rapid mixing of freshwater with marine water (see 3.2.4.1), increased turbidity (and thus decreased light) associated with the stormwater is a potential cause of seagrass decline. The cumulative impact of increased turbidity will depend on the level and duration of light reduction associated with the pulses of turbidity.

Light is one of the most important factors regulating the depth distribution of seagrasses; the lower depth limit of a seagrass species essentially provides an integrated measure of the minimum amount of light required for long-term survival. Results from laboratory experiments indicate that periods of very low light can be detrimental to the health of *Posidonia* and *Amphibolis*. In addition, results from light loggers deployed in Holdfast Bay indicate that light levels at 3m depth following significant rainfall events can decline to levels lower than those found at a depth of 18m depth, which is the lower depth limit of *Posidonia* in the region. This suggests that, at least for short-term periods, the amount of photosynthetically available light in the nearshore area of Holdfast Bay is less than the long-term requirement. However, over an annual basis, the amount of light reaching the seabed at 3m depth was still far greater than that in deeper waters. Nonetheless, the light environment in the shallow waters is highly variable and this may place a stress on seagrasses. Thus, the nearshore Adelaide coastal waters represent a poor environment in terms of optical quality, and these conditions, whilst they may not be solely responsible for seagrass loss in the area, represent a significant stressor, which may, in conjunction with another factor, be responsible for broadscale seagrass losses.

3.2.5 Seagrass dynamics / ecology

3.2.5.3 Are seagrasses sensitive to salinity changes – What is tolerance range of Adelaide's seagrass species

Adult plants of *Amphibolis antarctica* and *Posidonia sinuosa* were considered in terms of their response to short (72 hours) and long-term (seven weeks) exposure to salinities as low as 0 ppt. Both *A. antarctica* and *P. sinuosa* were highly tolerant to short-term reductions in salinity. Only after seven weeks of exposure to salinities of ~ 1 ppt were the plants essentially killed.

The viviparous seedlings of *A. antarctica* and the fruits of *Posidonia angustifolia* were also considered in terms of their tolerance to reduced salinity. Photosynthetic efficiency of *A. antarctica* seedlings was substantially reduced after short-term (72 hours) exposure to salinities below ~ 5 ppt. Although none of the test specimens was killed by the salinity dilution, it may well be expected that survival after more prolonged exposure would be limited. *Posidonia angustifolia* fruits were sensitive to reduced salinities, with high levels of mortality at salinity levels of 10 ppt or less for a period of 72 hours.

3.2.5.8 Is the seagrass loss we see a result of heavy chemical and pesticide/herbicide use in the catchments and coastal zones during past decades (e.g. 1960s - 1980s)?

While there is little historical information available on levels of potential toxicants entering, or present in, Adelaide's coastal waters, all reported levels (including those for Task EP 1 of the ACWS) have been very low or below detectable limits. Furthermore, the known levels of chemical exposure required to affect seagrass health are highly unlikely to occur off Adelaide's coastal waters due to rapid dilution. Even if harmful levels did occur in land-based discharges, any effects would only be seen on a very localised scale around the point of discharge and could not explain the large-scale historical losses seen off Holdfast Bay during past decades.

3.2.5.10 Is it possible to get the seagrasses back and what effect will this have on coastal processes, sand dynamics and movement?

SARDI Aquatic Sciences and the SA Department for Environment and Heritage are working together on a research project attempting to successfully restore Adelaide's seagrass meadows.

There are two possible ways in which seagrasses can return to areas of loss; natural recolonisation, and rehabilitation. Natural recolonisation of seagrasses has been observed at the disused sewage sludge outfall off Semaphore (Bryars and Neverauskas 2004) and in other isolated areas along the coast. However, natural recolonisation is unlikely in many areas along the Adelaide coastline where sediments are highly mobile and land-based discharges are still present (Seddon 2002). Moreover, in areas where natural recolonisation can occur or is occurring, recovery of large areas is likely to take many decades (Bryars and Neverauskas 2004).

Rehabilitation of seagrasses and other important habitats is generally viewed as a relatively new conservation strategy, but is beginning to gain more widespread acceptance. While seagrass rehabilitation efforts began was as early as 1947 in the United States, research in Australia on temperate species such as *Amphibolis* and *Posidonia* are far more recent. Many different transplanting and planting methodologies have been tested and developed, and in many cases success has been limited. In addition, rehabilitation has often proved to be extremely time consuming, and thus expensive, and is not feasible over large scales. One of the main reasons for rehabilitation failures in Southern Australia is high wave action; a factor that has previously tampered rehabilitation efforts in South Australia. In recognition of the need for a cost effective method of rehabilitation in high-wave energy environments that can be utilised over large scales, SARDI and DEH have been investigating recruitment facilitation methodologies. A range of hessian bags has been deployed in areas of seagrass loss along the Adelaide coast and results to date are extremely promising, with large numbers of *Amphibolis* seedlings recruiting on to the bags just weeks after deployment. The success of this type of rehabilitation is likely to be dependent upon a number of factors including proximity to *Amphibolis* seagrass beds and land-based discharges. Further research is needed before such techniques are utilised over large scales.

In summary, natural seagrass recolonisation is occurring at a few sites along the coastline. However, such a process will take many decades before any significant changes in seagrass coverage are observed. Moreover, natural recolonisation is unlikely in many areas including the denuded nearshore zone of Holdfast Bay. However, slow recovery may be observed if land-based discharges are reduced. Seagrass rehabilitation is likely to speed up the process of recolonisation in areas where conditions are conducive to natural recolonisation and may also be used in additional areas where natural recolonisation is not occurring.

Seagrass regrowth in many of the areas denuded in the past could be hampered by the changed seabed in these areas. In some places, no sand remains and the hard clay or calcrete base is exposed. In other areas, the bare sand is very mobile without the stabilising influence of existing seagrass and this could prevent seedlings securing themselves to the seabed. Seabed instability is exacerbated in nearshore areas by the reduced wave attenuation of bare sand compared with seagrass meadows (also discussed above), which means that wave-induced shear stresses might be greater on the seabed than in the past, despite the moderating effect of a deeper seabed.

Even if the coverage of Adelaide's offshore seagrass meadows was returned to its pre-European settlement extent, the ongoing erosion of the Adelaide coast would continue. The rate of erosion would be greater than at pre-European levels but less than present levels. Although increased coverage of seagrass would increase the attenuation of waves approaching the coast, the seabed would not have recovered to the elevations prior to seagrass loss and subsequent deepening of the seabed. Because of the deeper seabed, the seagrass would not attenuate the waves as much as would occur in shallower waters. Furthermore, there would be little discernable effect on wave refraction compared with the current situation until the slow rate of sediment trapping by the seagrass could significantly rebuild the seabed. The historic rate of accretion was estimated to be 0.6-0.7mm per year in Holdfast Bay by Thomas and Clarke (2002).

In summary, while the scale of sand movement and therefore management actions would be reduced by, as a best case, instantaneous seagrass recovery, active beach management would still be needed at a level somewhere below current levels but still greater than the intervention needed if the seagrass had not been lost in the first place.

3.2.5.11 Is recolonisation of seagrass dependent on the existence of a residual seagrass root mat?

SARDI and DEH have been investigating recruitment facilitation methodologies and results of their work help answer this question. The recolonisation of seagrass species into denuded areas is likely to be affected by a number of factors, including whether or not the original source of impact is still present, environmental conditions at the site of interest (such as wave energy, currents and sand movement), and seagrass species.

Recolonisation of seagrass is highly dependent upon whether or not the source of impact that resulted in seagrass loss is still present, and is the reason why a number of previous seagrass rehabilitation efforts have failed. Notwithstanding this, in areas where the source of impact has been removed, rehabilitation efforts have been more successful, and recolonisation of an area is more likely. For example, natural recolonisation of seagrasses has recently been observed in the bare sandy area surrounding the disused sewage sludge outfall off Semaphore (Bryars and Neverauskas 2004). This area does not have a remnant, viable *Posidonia* root mat. Thus the recolonisation is via seedlings rather than regrowth from the old root mat.

Environmental conditions are also likely to affect seagrass recolonisation. Along the Adelaide coast the loss of seagrasses in inshore areas has destabilised the coastline and increased sediment remobilisation. Consequently, the natural recruitment of seedlings into these highly mobile sandy areas is rare (Seddon 2002). Recent research has suggested that the natural recruitment of *Amphibolis* seedlings (which are released from the parent plant with a 'grappling apparatus' for attachment) is possible through the provision of suitable artificial substrates (e.g. hessian bags and strips). In these trials, hessian bags have recruited up to 495 seedlings per m^2. Thus the existence of an exposed residual seagrass root mat may play a similar role to the artificial substrates and is likely to increase the rate of recolonisation of seagrasses compared with sandy substrate with no residual seagrass root mat.

Bryars, S. and Neverauskas, V. (2004) Natural recolonisation of seagrasses at a disused sewage sludge outfall. *Aquatic Botany*. 80: 283-289.

Seddon S. 2002. Issues for seagrass rehabilitation along the Adelaide metropolitan coast: An overview. *In:* Seddon S. and Murray-Jones S. Eds. *Proceedings of the seagrass restoration workshop for Gulf St Vincent 15-16 May 2001.* Department of Environment and Heritage and SARDI Aquatic Sciences, Adelaide, pp. 1-8.

3.2.5.12 Are nutrients from WWTP outfall discharges the only cause of epiphytism on seagrass and is epiphyte loading the sole cause of smothering and demise of affected plants / communities?

Epiphytes are naturally occurring plants and animals that live on the aboveground surfaces of seagrasses. The ratio of epiphyte biomass to seagrass biomass (or plant surface area) is often referred to as the epiphyte load. Thus, an increased amount of epiphytes results in an increased epiphyte load. The epiphyte load seen on a plant is a complex interaction of many factors, including light, temperature, nutrients, grazing pressure, hydrodynamics, and propagule supply. Consequently, seagrasses display a wide range of epiphyte loads in the natural environment. Nonetheless, many epiphytes are opportunistic species that will thrive under certain environmental conditions, and it has been clearly shown that increased nutrient levels in the water column can cause an increase in epiphyte load and epiphyte composition.

Increased epiphyte loads and changes in epiphyte composition can potentially affect seagrasses by reducing the available light reaching a plant's photosynthetic surfaces, competing for nutrients, disrupting nutrient and gaseous exchange across the leaf surface, and increasing drag. It is widely believed that a decrease in light is the most harmful effect of increased epiphyte load. Nonetheless, it is possible that increased epiphyte loads were not the only cause of historical losses in the Holdfast Bay area. Stormwater discharges clearly cause a reduction in light in nearshore areas of Holdfast Bay and this may also have contributed to historical seagrass losses.

Prior to European settlement, the nutrient status of Adelaide's coastal waters was probably similar to the present status of most other parts of Gulf St Vincent, i.e. low in levels of nutrients or 'oligotrophic'. However, due to various land-based discharges operating along

Adelaide's coastline since the 1940's, significant nutrient inputs have occurred and Adelaide's coastal waters are no longer pristine or oligotrophic. While nutrient inputs occur from both WWTP outfalls and stormwater discharges, the relative contribution of WWTP outfalls is far greater than that from stormwater. Historically, it is likely that both WWTP and stormwater discharges contributed to an increase in epiphyte loads of nearshore seagrasses. It is quite possible that these increased loads contributed to a decline in nearshore seagrasses. However, it is impossible to determine the relative contribution of WWTP and stormwater discharges to those epiphyte loads.

3.2.5.13 Is the time of year when discharges occur important in terms of effects on marine impacts? - i.e. can you sustainably discharge in winter and not summer during algal growth periods?

This issue is closely related to 3.2.6.1. Epiphytic and drift algae are fast turnover, opportunistic species that are unlikely to store energy reserves. Growth of these algae is likely to be enhanced by higher levels of light and temperature found in summer. Thus it is expected that, if given the same nutrient levels, epiphytic and drift algae will grow faster in summer than winter. However, results from tank and field experiments indicate that if given nutrients during winter, growth of epiphytic and drift algae will be enhanced above normal rates.

3.2.6 Algal blooms

3.2.6.1 What is the link between nutrient discharges and brown algal blooms (particularly Giffordia)?

Giffordia is a previously recognised brown algal genus of five species (Womersley 1987). Species formerly belonging to this genus have been transferred to the genus *Hincksia* J.E. Gray. Of the five species recorded in southern Australia, four are recorded in South Australia. The genus belongs to the family Ectocarpaceae, order Ectocarpales, and as such, are characterised by a fine filamentous thallus. They may be epilithic (attached to the substrate), epiphytic (attached to other plants, such as seagrasses) or form loose free-floating aggregations. Species, or even genus, level identification is made difficult by the necessity of reproductive material, which is not always present.

Throughout the world, algal blooms of various taxa have been associated with excessive eutrophication (Morand and Merceron 2005, Cosser 1997). Other features commonly associated with bloom conditions are high light and high temperature. Filamentous algae such as those taxa represented in the Ectocarpales have a high surface area to volume ratio, which provide a mechanism for rapid uptake of nutrients (although see Lotzke and Schramm (2000) for an alternative).

In Australia, blooms of *Giffordia* have been recorded in various locations and different forms. In Botany Bay, Bell and Westoby (1987) describe the negative effects of *Giffordia* as a seagrass epiphyte on various ecosystem features (seagrass, fish, invertebrates etc). Off the coast of Adelaide, *Giffordia* is known to occur in bloom conditions in midsummer (Edyvane 1996, 1999).

It is worthy of note that at SARDI Aquatic Sciences, an experiment to investigate the interactive effects of light and nutrients on seagrasses also provided information on filamentous brown algal growth. As no reproductive structures were evident, identification to species level was not possible. However, the species did belong to the family Ectocarpaceae, and as such, is consistent with *Hincksia*. After 6 weeks of treatment at one of two of levels of nutrients (ambient and with the addition of 5mg/L $NH3$ & 1mg/L PO_4.) and light (equivalent to 3m, 7m and 18m depth), the levels of free floating algae were subjectively assessed and given a relative score out of ten (Figure 1). It is clear that even in the cold waters of winter, addition of nutrients can result in increased filamentous brown algal growth, so long as adequate light is available. Given that this algae tends to float, enough light will be available (surface light levels being even higher than the three metre depth equivalent used here).

Without a more focussed research effort, the question cannot be answered definitively. However, all the evidence available points to the fact that increased nutrient levels have the ability to promote the growth of nuisance filamentous brown algae such as *Hincksia*.

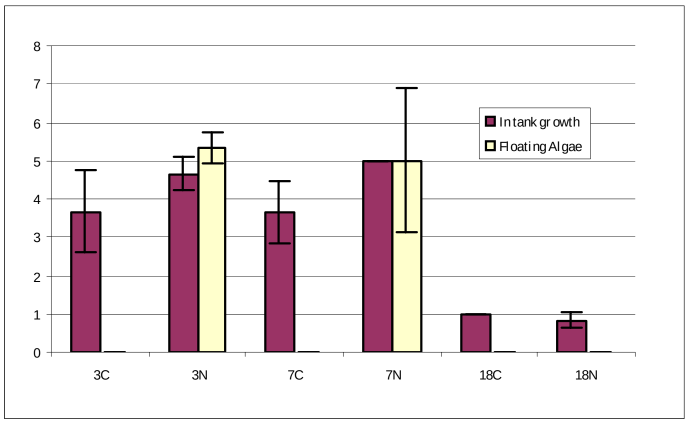

Figure 1: Relative levels of filamentous algae. These scores are averages of three replicate tanks and represent a subjective score out of ten. On the x-axis, the number represents the depth (3, 7 or 18m) and the letter indicates whether it is a control "C" or nutrient added "N" treatment. Error bars represent standard deviation. Most of the biomass measured here is brown filamentous algae, although some *Cladophora* was present. "In tank growth" refers to algae attached to the side of the tank.

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