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Seagrass rehabilitation in Adelaide's coastal waters VI. Refining techniques for the rehabilitation of *Amphibolis* spp.

Prepared for the Coastal Management Branch of the
Department for Environment and Heritage SA



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Government
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EXECUTIVE SUMMARY

Seagrass beds are critical coastal features across temperate and tropical latitudes, enhancing coastal productivity and nutrient cycling, providing habitat for a multitude of flora and fauna, and also stabilising sediments to reduce coastal turbidity. Like many coastal cities, the metropolitan waters of Adelaide have experienced substantial seagrass loss (more than 5200 ha since the 1950s). However, improvements to waste water management and quality have increased the probability for successful seagrass rehabilitation efforts, with recent studies identifying hessian bags placed near natural seagrass beds as a useful tool for artificially enhancing natural recruitment of *Amphibolis* spp.

Once identified, appropriate rehabilitation techniques can be refined in the context of the ecology of the target species, improvements to the design of recruitment units to maximise facilitation of new recruits, as well as solving unforeseen issues that arise only through trial of new techniques. The specific aims of the research described herein were to:

- Identify the timing of *Amphibolis* recruitment on hessian recruitment units
- Better understand spatiotemporal patterns in the recruitment of *Amphibolis* to hessian units
- Refine the design of recruitment units by testing the effects on recruitment, if any, of variation in (a) the type of material used to fill hessian bags, and (b) the layout of recruitment units on the sea floor
- Trial different coating methods designed to improve the longevity of hessian and thus maximise chances for rehabilitation success.
- Develop a map of light availability using data from the Adelaide Coastal Waters Study as a first step towards developing a map of site suitability for seagrass rehabilitation.

Sustained bi-monthly deployment of hessian recruitment units over ~ 15 months identified a strong *Amphibolis* recruitment event, beginning June/July 2008 and continuing until at least September 2008. However, recruitment was spatially variable, with good to strong recruitment observed at the southern sites off Brighton and Grange, while poor recruitment was observed at the northern sites off Semaphore and Largs Bay.

Filling hessian bags with sand instead of rubble produced no statistically significant effect on the recruitment of *Amphibolis*, while single isolated hessian bags on the sea floor appeared to be just as effective (if not more so) at facilitating recruitment on a per unit area basis as five bags grouped together.

Previous studies using hessian bags have identified the degradation of hessian as a potential limitation on the recruitment of *Amphibolis*. Coating bags with two different polymers (organosilane and polyurethane) has shown that polyurethane facilitates less recruitment, although the experiment has only recently been established and further sampling is needed to reach definitive conclusions.

Modelling the light environment showed that water clarity was strongly related to depth, with the least turbid conditions found at deeper offshore locations. The percentage transmission of surface light to the seafloor was consequently low in shallow turbid waters, peaked at ~ 14 % at a depth of ~ 3.5 m, before gradually decreasing as depth increased. Among site variability (Brighton to Grange) appeared negligible.

This research provides information that improves the probability for successful rehabilitation of *Amphibolis* in Adelaide's metropolitan coastal waters. Deploying hessian recruitment units immediately prior to and during the peak period of recruitment (~ June/July – September) appears a logical and cost-effective practice, particularly at sites where high numbers of recruits are observed (e.g. Brighton and Grange), and between certain depths (e.g. 3.5 – 18 m) where average light availability is adequate for seagrass growth. For the recruitment units themselves, using hessian bags filled with sand and placed as an isolated unit again appears a simple and cost-effective strategy. It is too early to provide definitive conclusions on the use of polymer coatings to slow hessian degradation, but this work shows great promise.

While this research provides several steps forward, further work is certainly needed to improve our understanding of the ecology of *Amphibolis* and other seagrasses on Adelaide's coasts. Identifying suitable sites for rehabilitation is critical, and will require further work to model the physical conditions along the coast, as well as a better understanding of spatiotemporal variability in recruitment events (or lack thereof) and identifying causes of recruitment failure. More work to improve the design, use, and longevity of the hessian recruitment units is also warranted, such

that future large-scale and costly rehabilitation efforts are done with maximum probability of success.

Chapter 1. Improving ecological and methodological understanding to enhance *Amphibolis* recruitment

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1.1 INTRODUCTION

Many of the Earth's most extensive habitats are created by living organisms such as trees, mangroves, seagrasses, kelps, and corals (Jones et al. 1994; Grutter & Irving 2007). The importance of such organisms is underlined by their facilitation of numerous taxa that often form critical links in food webs and would otherwise be rare or entirely absent (Graham 2004), their enhancement of ecosystem-level properties such as large-scale primary production and nutrient cycling (Stachowicz 2001), and ultimately, their provision of natural resources and services that sustain human populations and fuel national economies (Costanza et al. 1997). Given such benefits, it is not surprising that substantial concern arises over the fragmentation and loss of biogenic habitats, particularly in urban centres where a legacy of resource exploitation and environmental impacts has typically altered natural conditions and promoted extensive habitat loss (Vitousek et al. 1997; Jackson 2001; Connell 2007).

One major coastal habitat found in tropical and temperate seas throughout the world is seagrass beds. Seagrasses often form extensive and highly productive habitats (Hillman et al. 1989) that grow in soft-sediment environments (e.g. beaches and estuaries) and by doing so add considerable structural complexity to otherwise uniform landscapes (Robbins & Bell 1994). This structure is utilised by an abundant and diverse range of flora and fauna (Edgar 1990; Heck et al. 1995; Connolly 1997), including juveniles of many species of fish and invertebrates of commercial importance (e.g. King George whiting: Connolly 1994, Tiger prawns: Loneragan et al. 1998). Additionally, seagrass beds may assist in the reduction of excessive nutrient loads (Connell & Walker 2001) and modify local hydrodynamic conditions by slowing water flow among leaves and thereby entraining and trapping sediments (Terrados & Duarte 2000). In combination with their below-ground root-rhizome biomass,

seagrass beds can greatly stabilize sediments and thus enhance water quality by reducing coastal erosion and turbidity (Orth 1977).

Like many urbanized coasts around the world (see review by Walker et al. 2006), seagrass has undergone substantial population decline off the metropolitan coast of Adelaide, South Australia. Since the 1950s, it is estimated that more than 5200 ha of seagrass has been lost (Seddon 2002), with poor water quality resulting from high turbidity and excessive nutrient loads being identified as the primary causes (Bryars et al. 2006; Collings et al. 2006a; 2006b). Water quality has improved in recent years, with some evidence of natural seagrass recovery providing encouraging signs that environmental conditions are now conducive to successful rehabilitation efforts (Bryars 2008).

Habitat rehabilitation can be a useful tool for artificially supplementing natural rates of recruitment within degraded populations, or for re-establishing populations that have been lost entirely. Rehabilitation of seagrass beds has been attempted for many years with mixed success, but appears an important pursuit given the rapid and devastating impacts human activities can have on seagrass populations, and their typically slow recovery time (e.g. in the order of decades to hundreds of years: Kirkman & Kuo 1990; Bryars & Neverauskas 2008). Seagrass rehabilitation often involves the translocation of adults from source populations into target areas (Fonseca et al. 1996; Bell et al. 2008), though care must be taken to ensure the source population is not altered through over-harvesting to the point where it also becomes a fragmented system. An alternate approach is to focus on early life-history stages (seeds and seedlings), using techniques that enhance natural rates of recruitment (e.g. artificial recruitment structures), or supplementing natural recruitment with artificially-reared individuals (e.g. seedling propagation). This approach is attractive because it minimizes harm to extant adult populations, and can potentially expand populations over greater areas and in less time than individually transplanting adults.

Previous work to restore seagrass off Adelaide's metropolitan coast has demonstrated considerable potential for enhancing natural rates of recruitment for the seagrasses *Amphibolis antarctica* and *A. griffithii* using artificial recruitment structures made from hessian material, particularly sand-filled hessian bags (Wear et al. 2006; Collings et al. 2007; Collings 2008). Hessian bags placed near natural seagrass beds have facilitated the recruitment of up to ~ 140 seedlings m⁻² after 12

months (Wear et al. 2006), although substantial among-site variability in recruitment can occur (Collings et al. 2007). Additionally, this earlier research highlighted issues with hessian durability that need to be resolved before any large-scale seagrass rehabilitation attempt can be made with confidence.

The encouraging signs shown in these earlier experiments have generated a need to better understand the fundamental recruitment dynamics of *Amphibolis* spp., refine the design of the hessian recruitment units to maximise recruitment success, and improve the durability of hessian to provide enough time for recruits to become established in their own right (i.e. self-anchoring through root-rhizomes). In this context, the specific aims of the current study were to:

- Identify the timing of *Amphibolis* recruitment on hessian recruitment units
- Better understand spatiotemporal patterns in the recruitment of *Amphibolis* to hessian units
- Refine the design of recruitment units by testing the effects on recruitment, if any, of variation in (a) the type of material used to fill hessian bags, and (b) the layout of recruitment units on the sea floor
- Trial different polymer coating methods designed to improve the longevity of hessian and thus maximise chances for rehabilitation success.

1.2 METHODS

1.2.1 Study sites

Four sites off the metropolitan coast of Adelaide were chosen for experiments: Brighton (35.01382° S, 138.30132° E), Grange (34.54249° S, 138.28248° E), Semaphore (34.52279° S, 138.27476° E), and Largs Bay (34.49954° S, 138.26837° E) (Fig. 1.1). These sites were chosen because of i) the presence of natural *Amphibolis* beds that may serve as a source of recruits, ii) the presence of nearby unvegetated sand patches upon which recruitment units could be placed, iii) ease of access for relocation and repeated sampling, and iv) previous studies that have identified these sites as good candidates for seagrass rehabilitation research (e.g. Wear et al. 2006; Collings et al. 2007; Collings 2008).

All sites were ~ 2 – 4 km offshore, separated from each other by 3 – 14 km, and experiments were done at ~ 7 – 8m depth. Hessian recruitment units (see description below) were positioned on sand either adjacent to edges of natural

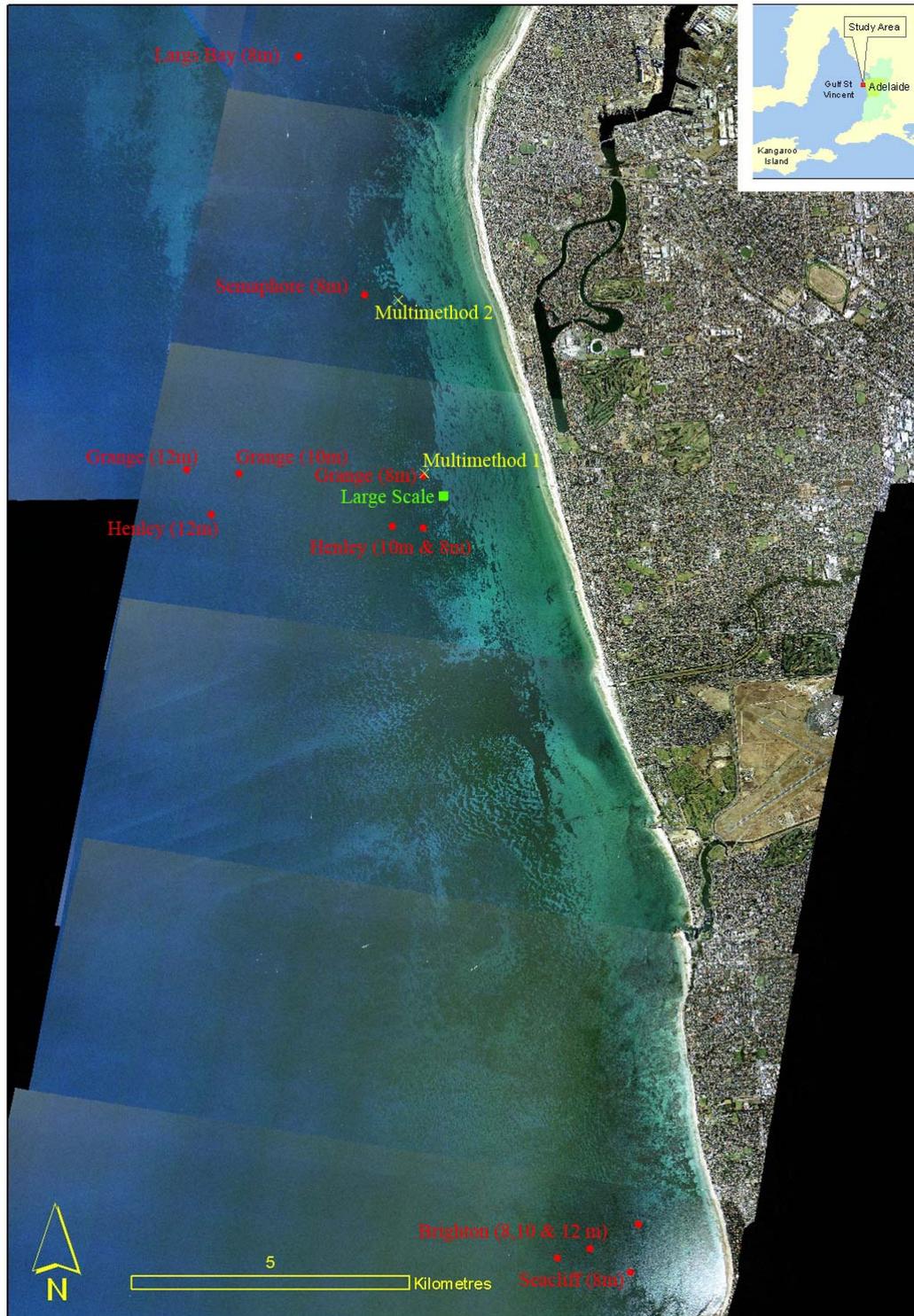


Figure 1.1 Map of the metropolitan coast of Adelaide showing the locations of sites used in experiments (Brighton, Grange, Semaphore, and Largs Bay, all at 8m). Other points on the map show locations of prior experiments described in Wear et al. (2006), Collings et al. (2007), and Collings (2008). Aerial photograph from the S.A. Department for Environment and Heritage.

seagrass beds (i.e. inshore from the seagrass beds) or on sand patches within seagrass beds, and were individually tagged for relocation. All sites support natural populations of *Posidonia* spp. and *Amphibolis* spp., particularly *A. antarctica*, and less commonly, *A. griffithii* (Bryars & Rowling 2008).

1.2.2 Hessian recruitment units

In all experiments, hessian bags were used as the recruitment surface for *Amphibolis* spp. Hessian bags have been developed as a useful method for *Amphibolis* recruitment because the grappling hook structure at the base of water-borne seedlings becomes entangled in the hessian and helps to anchor new recruits as the bag sinks into the sand and stabilizes (Fig. 1.2a). Hessian bags also have the added advantage of being biodegradable over time, eliminating the need to retrieve structures used to initially facilitate recruitment, as well as any likely disturbance to the restored seagrass populations during retrieval activities. Note that although *Posidonia* spp. are present in natural beds at all study sites, their recruitment is not directly facilitated by hessian bags because of different life-histories (vivipary in *Amphibolis* vs seeds in *Posidonia*) and because they do not possess a grappling hook structure.

Recent work off metropolitan Adelaide has tested the effectiveness of various hessian structures for the recruitment of *Amphibolis* spp. Results show that one of the most biologically- and cost-effective methods is to use a fine-weave hessian bag filled with sand and entirely covered by a layer of coarse-weave hessian (Fig. 1.2b, c) (Wear et al. 2006). This design was used as the standard recruitment unit for all experiments described below. Each bag measured ~ 0.76 × 0.46 m and was filled with ~ 23 – 25 kg of clean coarse builders sand (with the exception of one experimental test: see 'Type of filling' below). For all experiments, no attempt was made to distinguish between recruits of *A. antarctica* and *A. griffithii*, given the difficulty of accurately making the required *in situ* observations of new recruits and the need to sample experiments non-destructively. However, most recruits were likely to be *A. antarctica* given the relative dominance of this species in natural seagrass beds along Adelaide's metropolitan coast (Bryars & Rowling 2008).

1.2.3 Timing of recruitment

The timing of *Amphibolis* recruitment was determined by deploying ten new hessian bags along the inshore edge of the natural seagrass bed at Grange ~ every 2 months for 15 months (Sep 2007 – Nov 2008). New bags were deployed on each occasion

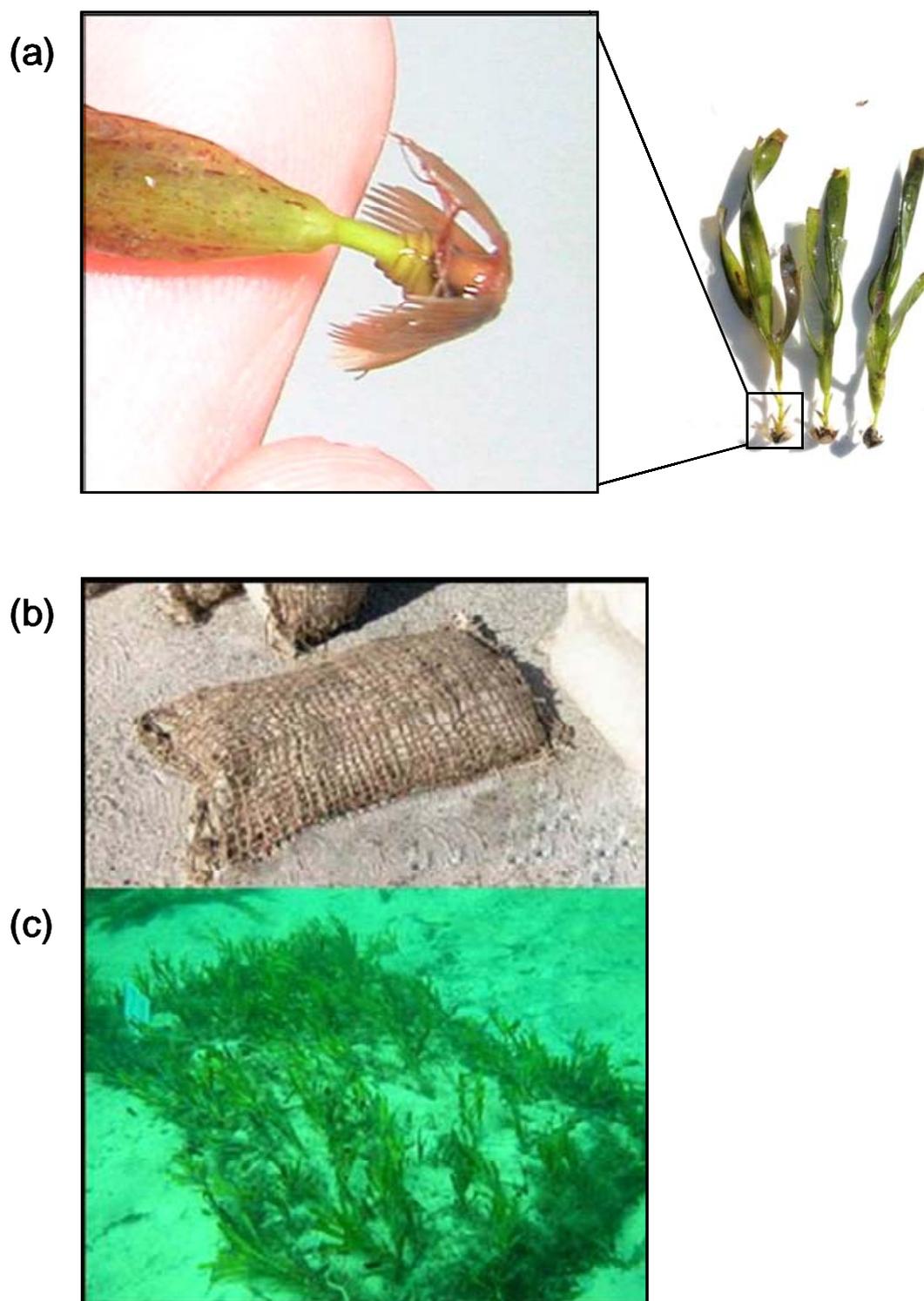


Figure 1.2 (a) Detail and position of grappling hook at the base of *Amphibolis* seedlings. (b) Image of hessian bags with outer weave of coarse hessian used in experiments, and (c) image of bags supporting *Amphibolis* recruits. All images from Collings et al. (2007).

because hessian degrades over time, likely reducing the potential for older bags to facilitate recruitment relative to younger bags, which may ultimately result in older bags 'missing' recruitment events.

Bags were first deployed on the 5th of September 2007. At each of the six subsequent deployments of new bags, the abundance and height of *Amphibolis* recruits growing on bags from all previous deployments were sampled non-destructively by divers. Abundance was quantified by counting all individuals on each bag, while height was sampled by haphazardly choosing, when available, at least one individual per bag (usually three to five) and measuring the distance from the sand surface to the tip of the plant. The mean value of these height measurements within each replicate bag was calculated and used as a single replicate for statistical analyses. All analyses were done using the SYSTAT 11.0 statistical package (Systat Software Inc.). For significant effects of treatments with three or more levels, *post-hoc* comparisons to identify the location of detected differences were done using Tukey's honestly significant difference test.

1.2.4 Spatiotemporal patterns

Spatiotemporal patterns in the recruitment of *Amphibolis* to hessian bags were identified by deploying bags at each of the four sites described above. On the 5th of September 2007, ten bags were deployed at each site except for Grange (nine bags), with the abundance and height of recruits on all bags sampled non-destructively ~ every 2 months for 15 months as described above. Analysis of spatiotemporal patterns in *Amphibolis* density and height was done using repeated-measures ANOVA, treating 'time' (seven levels) as the within-subjects factor, and 'site' (4 levels) as a fixed and orthogonal between-subjects factor.

1.2.5 Type of filling

Testing the effect of the type of filling within the hessian bag on recruitment was done at two sites (Brighton and Grange) using bags either filled with sand (clean, coarse builders sand) or a mixture of sand and rubble (20 mm quartzite aggregate) (~ 23 – 24 kg per bag). Ten bags (Brighton) or nine bags (Grange) of each type of filling were deployed on the 5th of September 2007, and were subsequently sampled ~ every 2 months for 15 months as described above. Analysis of *Amphibolis* density and height among treatments was done using repeated measures ANOVA, treating 'time' (seven levels) as the within-subjects factor, and 'site' and 'filling' (2 levels each) as fixed and orthogonal between-subjects factors.

1.2.6 Layout

To test whether the layout of recruitment units influences *Amphibolis* recruitment, hessian bags were arranged either as a standard single isolated bag ($n = 9$ replicates), as a 'stack' of bags that provided some vertical relief, or as a group of 'flat' bags with the same vertical relief as a standard isolated bag ($n = 5$ replicates of stacked and flat treatments). Stacked units were constructed by building a base of four individual hessian bags side-by-side to form a 2×2 grid, and then placing a fifth bag on the top and centre of the base (i.e. adding vertical relief). Flat units were constructed using the same four-bag base, but then placing the fifth bag at one edge to create recruitment units with relatively low vertical relief but with approximately the same surface area for recruitment as stacked units. Two comparisons were made. First, the hypothesis was tested that a group of five bags (stacked and flat treatments) would recruit more *Amphibolis* per unit area than a single isolated bag. Secondly, the hypothesis was tested that bags with greater vertical relief (stacked treatment) would recruit more *Amphibolis* than those with less vertical relief (flat treatment).

All bags were deployed at Grange on the 5th of September 2007, and were sampled as described above ~ every 2 months for 15 months. Analysis proceeded using repeated measures ANOVA, treating 'time' (seven levels) as the within-subjects factor, and 'layout' (3 levels) as a fixed and orthogonal between-subjects factor.

1.2.7 Hessian coating trial

Efforts to improving the durability of hessian bags involved coating them with non-toxic and ultra-thin silicon-based polymers prior to their deployment (in collaboration with Drs Jamie Quinton and Stephen Clarke, Flinders University). Such polymers are so smooth that even the adhesion of bacteria is weak, which inhibits the formation of a biofilm and thereby potentially enhances hessian longevity. In this experiment, bags were coated with one of two types of polymer, organosilane (of form $R'-Si(OR)_3$) or polyurethane, or were left as uncoated controls ($n = 30$ per treatment). All bags were deployed at Grange on the 18th of August 2008, and were sampled ~ 2.5 months later on the 30th of October as the first sampling of a long-term design. Analysis of *Amphibolis* density and height was done using one-way ANOVA.

1.3 RESULTS

1.3.1 Timing of recruitment

Recruitment of *Amphibolis* was negligible on all bags deployed during the first half of the trial period (Sep 2007 – May 2008: Fig. 1.3a). By July 2008, however, an obvious recruitment event had occurred at Grange, with all bags supporting much greater densities than previously sampled (up to ~ 600 individuals m⁻²). Recruitment seemed to continue until ~ September, since bags deployed on the 18th of August 2008 supported substantial recruit densities during sampling at the end of September (~ 400 individuals m⁻², Fig. 1.3a: 18-Aug-08 treatment), but relatively little recruitment was observed for bags deployed later (Fig. 1.3a: 29-Sep-08 treatment). By November 2008, densities on most bags had declined by 29 – 51 % of the maximum sampled.

During the recruitment event, bag age appeared to affect the resulting density of *Amphibolis* recruits, with younger bags generally facilitating the greatest recruitment (Fig. 1.3a: July sampling, ANOVA on this day: $F_{4,44} = 56.69$, $P < 0.001$, *Post-hoc* comparisons: 9-May-08 > 10-Apr-08 > 11-Feb-08 > 16-Nov-07 = 5-Sep-07). Observation of bags at this time showed that older bags were often degraded (e.g. loss of coarse outer weave and torn hessian) or already buried under sand, which likely limited their potential as a surface upon which *Amphibolis* seedlings could recruit.

The average height of *Amphibolis* seedlings increased with time as recruits grew in the early stages of the trial, but exhibited a sharp decline between April and May 2008 (Fig. 1.3b). Since this decline precedes the observed recruitment event beginning in June-July, it is likely due to the loss of larger individuals from bags rather than the influx of small new recruits. Following this decline, the average height of seedlings again increased through time on all bags to reach pre-decline levels (~ 13 – 15 cm) by September of 2008.

1.3.2 Spatiotemporal patterns

The density of *Amphibolis* recruits on hessian bags varied substantially over time and among sites (Table 1.1a). Over the first half of the experimental period, *Amphibolis* density was generally low at all sites and times, with an exception being a temporary increase of plant density at Grange during November 2007 (Fig. 1.4a). The recruitment event beginning in June – July (identified in the 'Timing of recruitment' experiment described above) was apparent particularly at Brighton and Grange, but

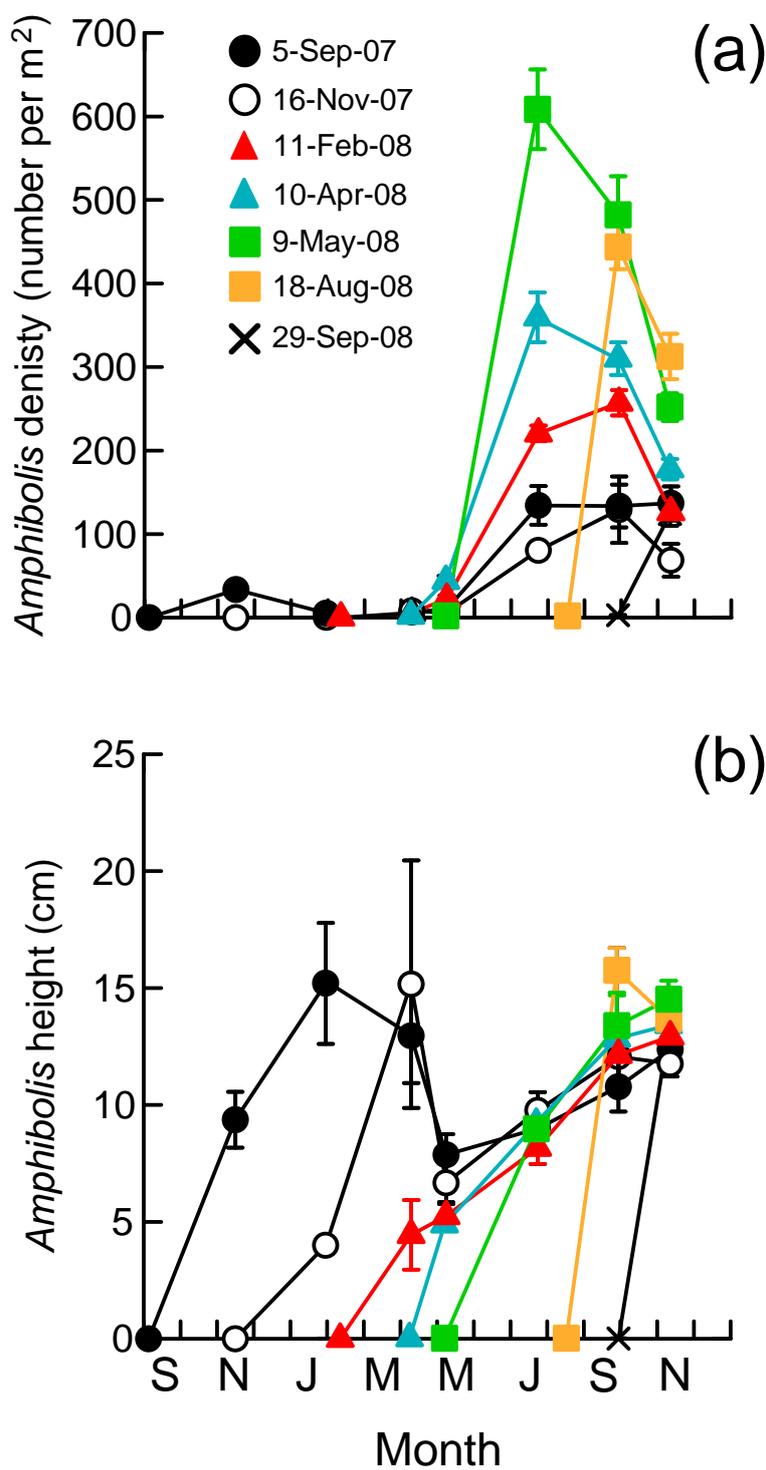


Figure 1.3 Results of experimental deployment of hessian bags to identify the timing of *Amphibolis* recruitment at Grange. Data show mean \pm SE (a) density of *Amphibolis* recruits through time, and (b) height of *Amphibolis* recruits through time. Data for each time of deployment are depicted with a different symbol/shading.

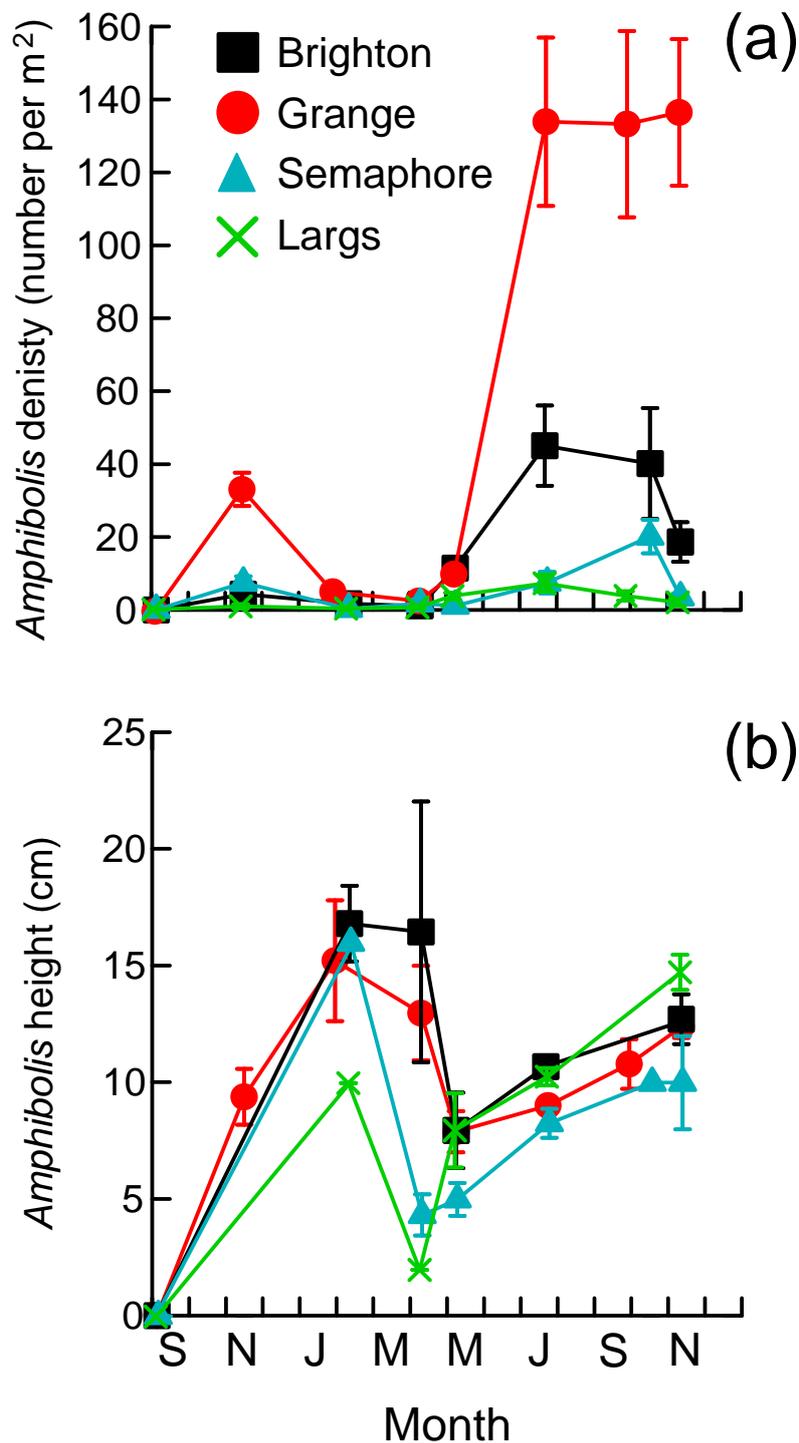


Figure 1.4 Results of experimental deployment of hessian bags to identify spatiotemporal patterns in the mean \pm SE (a) density of *Amphibolis* recruits, and (b) height of *Amphibolis* recruits. Hessian bags were deployed at 4 sites (each depicted with a different symbol) and were sampled over 15 months (Sep 2007 – Nov 2008).

Table 1.1 Results of repeated-measures ANOVA testing for differences in the (a) density, and (b) height of *Amphibolis* recruits on hessian bags among sites (Brighton, Grange, Semaphore, and Largs Bay) and over time ($n = 7$). Significant outcomes are shown in bold type. Note that the Greenhouse-Geisser epsilon-adjusted P -value was used for 'within-subjects' tests to account for any departures of sphericity among the data and to compensate for inflated Type I error rates (Myers & Well 2003).

Response	Source	df	MS	F	P
(a) density	Within-subjects				
	Time	6	12141.01	36.73	< 0.001
	Time x Site	18	4392.83	13.29	< 0.001
	Residual	174	330.57		
	Between-subjects				
	Site	3	27739.62	23.64	< 0.001
	Residual	29	1173.22		
(b) height	Within-subjects				
	Time	4	58.25	3.63	0.087
	Time x Site	12	19.90	1.24	0.376
	Residual	20	16.06		
	Between-subjects				
	Site	3	20.61	3.04	0.131
	Residual	29	6.79		

was largely absent at the two northernmost sites of Semaphore and Largs Bay. Correspondingly, *Amphibolis* densities increased greatly at Grange (up to ~ 134 individuals m^{-2}), moderately at Brighton (~ 45 individuals m^{-2}), but negligibly at Semaphore and Largs Bay (~ 7 individuals m^{-2}) during this period (Fig. 1.4a). Observation of bags prior to this recruitment event (April 2008) showed bags were largely intact at Brighton and Grange, but that most had lost their outer coarse weave at Semaphore and Largs Bay. Interestingly, densities exhibited a decline over the remainder of the experimental period at all sites except for Grange, which experienced the greatest recruitment of individuals and maintained these densities.

The average height of *Amphibolis* recruits was statistically similar among sites and over time (Fig. 1.4b, Table 1.1b), although plants at the two southernmost sites of Brighton and Grange appeared larger than at Semaphore and Largs Bay in April (13 – 16cm vs 2 – 4cm). As observed in the 'Timing of recruitment' experiment, height declined sharply at all sites between April and May (prior to the recruitment event) and increased thereafter.

1.3.3 Type of filling

Recruitment was typically low during the first half of the experiment, and so it is difficult to ascertain what effect the type of filling had during this time. However, following the June-July recruitment event, filling hessian bags with sand instead of rubble appeared to enhance the mean *Amphibolis* recruitment at Grange (~ 134 individuals m⁻² for sand vs 97 individuals m⁻² for rubble) but not at Brighton (~ 45 individuals m⁻² vs 26 individuals m⁻²) (Fig. 1.5a), although considerable variation among replicates resulted in the effect being non-significant (Table 1.2a). Again, greater overall recruitment was observed at Grange with these densities maintained through time, while densities at Brighton declined. Correspondingly, bags at Brighton appeared to undergo more degradation than bags at Grange.

Although the height of *Amphibolis* recruits varied through time (Fig 1.5b, Table 1.2b: Time main effect), it did not differ among sites and was unaffected by the type of filling, averaging ~ 12 – 13 cm across the duration of the experiment.

1.3.4 Layout

While the density of *Amphibolis* recruits varied through time (and again increased substantially during the June-July recruitment event), neither flat nor stacked experimental units (5 hessian bags per unit) facilitated different densities or heights of *Amphibolis* on a per area basis than single smaller isolated hessian bags (Fig. 1.6, Table 1.3). However, a trend developed over the last five months of the experiment that suggested isolated units retain recruits better than grouped units, since a 29 – 43 % decline in *Amphibolis* density occurred on grouped units during this period, which was not observed on isolated units (Fig. 1.6a). While this trend was not yet statistically significant, sampling of this experiment is continuing.

Testing the effects of vertical relief of recruitment units (flat vs stacked treatments) showed no effect on either *Amphibolis* density or height (Fig. 1.6), with both treatments producing strikingly similar effects.

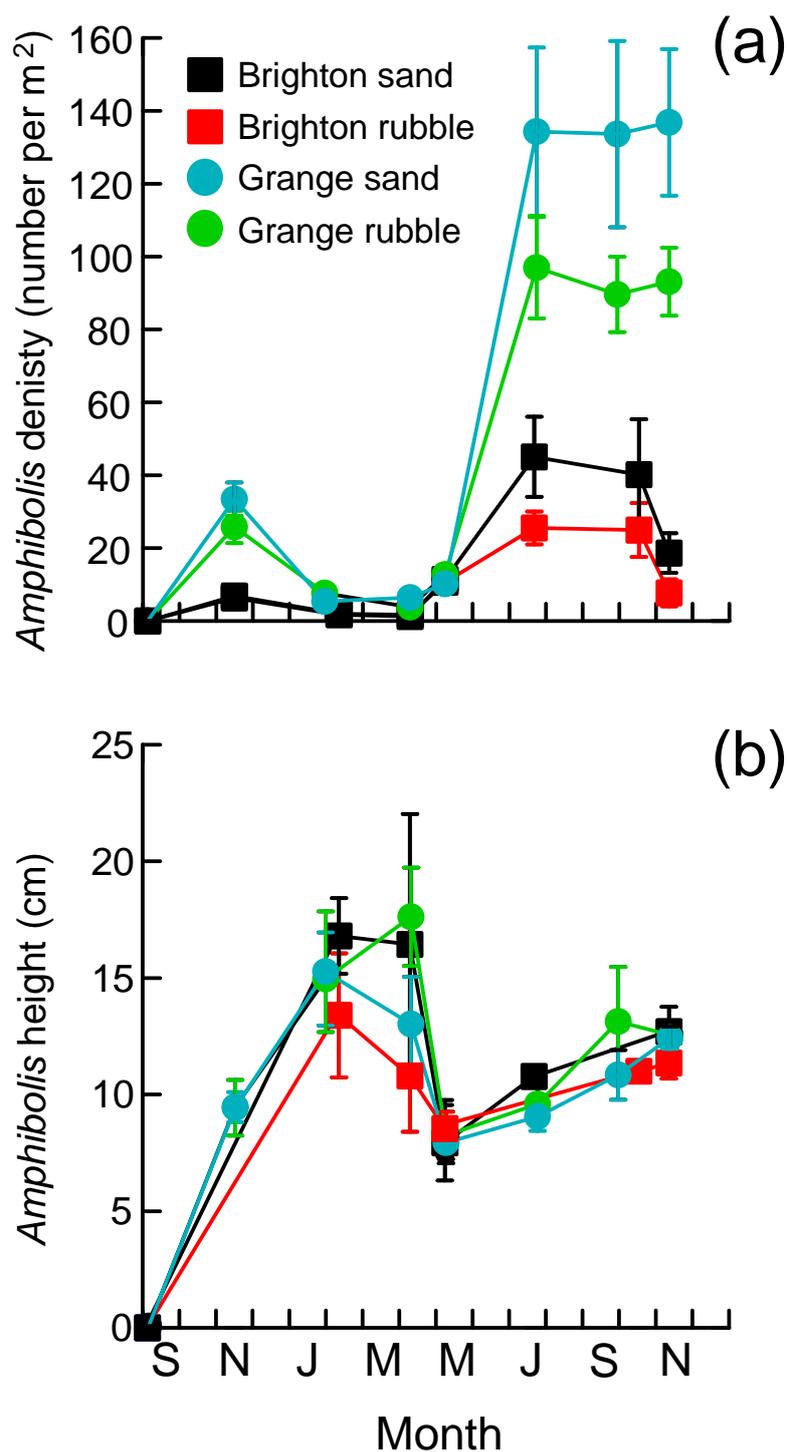


Figure 1.5 Effects of variation in the type of filling within hessian bags (sand vs rubble) on the mean \pm SE (a) density of *Amphibolis* recruits, and (b) height of *Amphibolis* recruits at two sites (Brighton and Grange) sampled over 15 months (Sep 2007 – Nov 2008).

Table 1.2 Results of repeated-measures ANOVA testing the effects of type of filling within hessian bags (sand vs rubble) on the (a) density, and (b) height of *Amphibolis* recruits between sites (Brighton and Grange) and over time ($n = 7$). As for table 1, significant outcomes are shown in bold type, and Greenhouse-Geisser epsilon-adjusted P -values were used for 'within-subjects' tests.

Response	Source	df	MS	F	P
(a) density	Within-subjects				
	Time	6	24067.91	49.45	< 0.001
	Time x Site	6	11521.44	23.67	< 0.001
	Time x Filling	6	1446.79	2.97	0.065
	Time x Filling x Site	6	860.53	1.77	0.184
	Residual	150	486.70		
	Between-subjects				
	Site	1	75868.53	45.96	< 0.001
	Filling	1	5658.92	3.43	0.076
	Site x Filling	1	3084.56	1.87	0.184
	Residual	25	1650.81		
(b) height	Within-subjects				
	Time	3	193.97	10.38	< 0.001
	Time x Site	3	12.64	0.68	0.528
	Time x Filling	3	4.45	0.24	0.807
	Time x Filling x Site	3	26.33	1.41	0.262
	Residual	39	18.67		
	Between-subjects				
	Site	1	12.13	0.67	0.428
	Filling	1	7.32	0.40	0.536
	Site x Filling	1	29.30	1.62	0.225
	Residual	13	18.09		

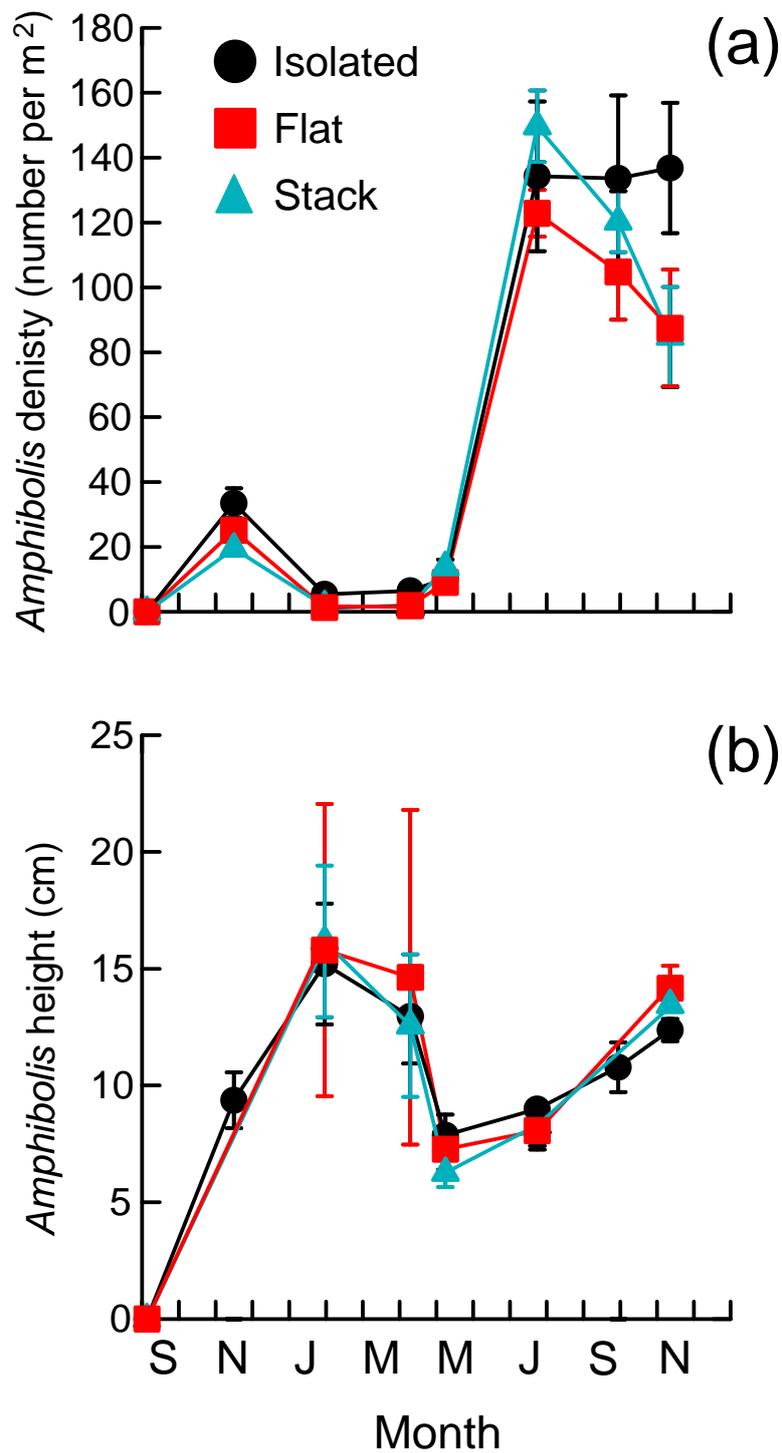


Figure 1.6 Effects of varying the layout of hessian recruitment units (stacked vs flat vs isolated bags) on the mean \pm SE (a) density of *Amphibolis* recruits, and (b) height of *Amphibolis* recruits sampled over 15 months (Sep 2007 – Nov 2008) at Grange.

Table 1.3 Results of repeated-measures ANOVA testing the effects of variation in recruitment unit layout (stacked vs flat vs isolated bags) on the (a) density, and (b) height of *Amphibolis* recruits at Grange and over time ($n = 7$). As for table 1, significant outcomes are shown in bold type, and Greenhouse-Geisser epsilon-adjusted P -values were used for 'within-subjects' tests.

Response	Source	df	MS	F	P
(a) density	Within-subjects				
	Time	6	48118.15	53.84	< 0.001
	Time × Layout	12	709.03	0.79	0.530
	Residual	66	893.76		
	Between-subjects				
	Layout	2	1426.54	0.43	0.663
	Residual	11	3348.25		
(b) height	Within-subjects				
	Time	4	109.28	3.23	0.088
	Time × Layout	8	17.57	0.52	0.671
	Residual	32	33.85		
	Between-subjects				
	Layout	2	2.31	0.061	0.941
	Residual	8	38.00		

1.3.5 Hessian coating trial

Substantial recruitment of *Amphibolis* was observed on all hessian bags (up to 250.87 ± 14.51 individuals m^{-2}) even though bags were deployed relatively late (August) in the observed recruitment period (~ June - September). By late October, bags treated with polyurethane supported 26 – 34 % lower densities of *Amphibolis* than bags that were either untreated or coated with organosilane, which did not differ from each other (Fig. 1.7a, ANOVA: $F_{2, 87} = 14.19$, $P < 0.001$, *Post-hoc* tests: none = organosilane > polyurethane). All bags appeared in good condition during sampling.

In contrast to density estimates, the type of coating had no effect on *Amphibolis* height (Fig. 1.7b, ANOVA: $F_{2, 84} = 2.88$, $P = 0.062$), with observed average heights among treatments (13 – 14 cm) similar to average heights observed in the other experiments.

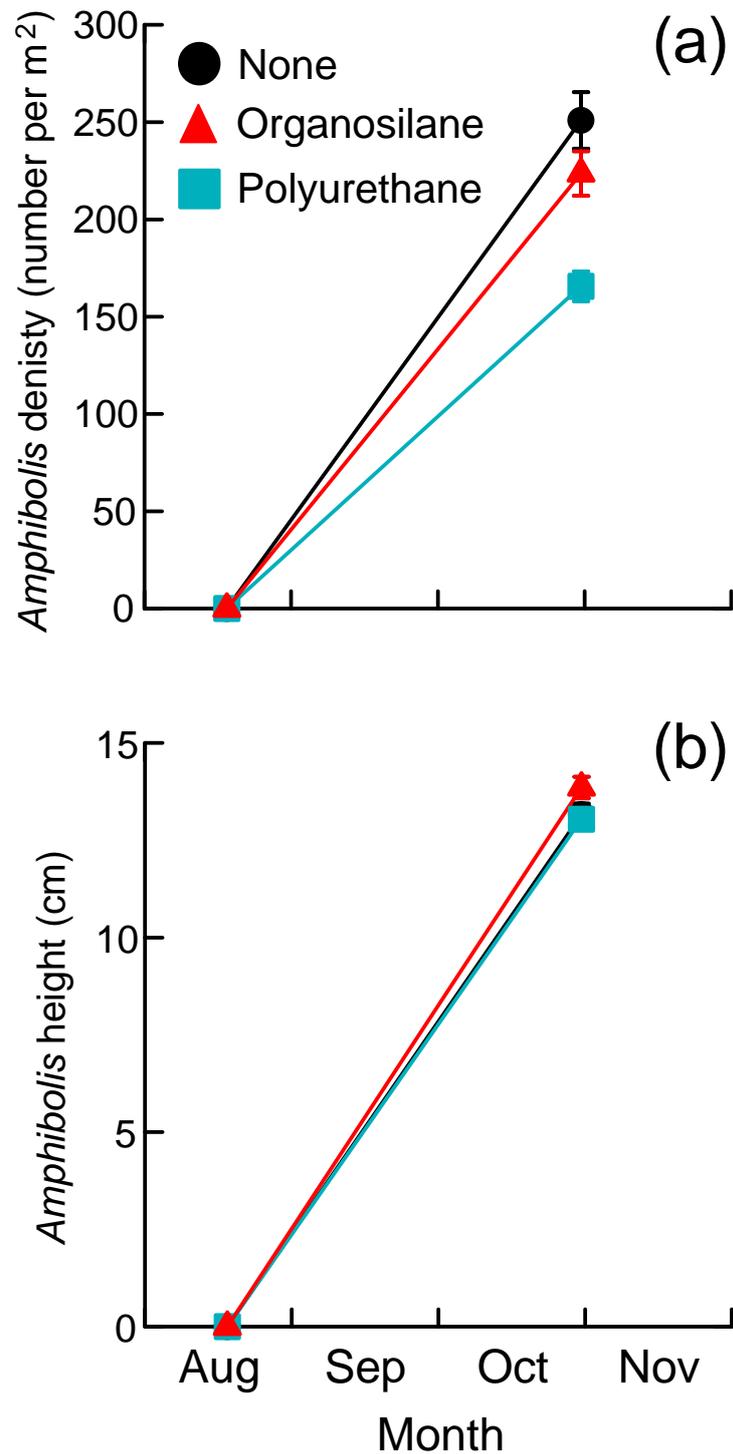


Figure 1.7 Effects of coating hessian bags with non-toxic ultra thin polymers (organosilane vs polyurethane vs no coating) on the mean \pm SE (a) density of *Amphibolis* recruits, and (b) height of *Amphibolis* recruits at Grange.

1.4 DISCUSSION

The fragmentation and loss of marine habitats is a major environmental issue in many countries, particularly around urbanized coastal regions where management of anthropogenic inputs and disturbances to marine systems have only become a priority relatively recently. As a tool to mitigate such impacts, habitat rehabilitation has become an important yet resource- and time-consuming exercise that has been attempted in a variety of systems with varying levels of success (e.g. Coen & Luckenbach 2000).

Rehabilitation techniques that enhance natural rates of recruitment have become popular as more biologically- and cost-effective methods have been developed. However, a sound understanding of the ecology of the early life-history stages of the target species (e.g. recruitment windows, environmental stressors) is always desirable in order to maximise the likelihood of successful rehabilitation. Unfortunately, we often know far more about the ecology of the larger adult stages than juveniles (Schiel & Foster 2006), potentially limiting our ability to design and implement rehabilitation techniques using juvenile stages with confidence.

A primary aim of the current study was to improve the likelihood of successful rehabilitation of seagrass off Adelaide's metropolitan coast by identifying periods of natural recruitment of a key seagrass genus (*Amphibolis*), as well as by understanding spatiotemporal patterns in recruitment at target locations for rehabilitation. Previous work has identified that *Amphibolis* release their seedlings between July and December each year (Robertson 1984). Using artificial hessian recruitment units, the current research also identified a strong *Amphibolis* recruitment event beginning in June/July and lasting until at least September. Importantly, this recruitment event was detected in multiple independent experiments. Observation of hessian bags throughout the year showed considerable degradation as bags aged, which clearly reduced their suitability as a surface for *Amphibolis* recruitment. Collectively, therefore, it appears that *Amphibolis* rehabilitation success will likely be maximized when new hessian bags are deployed from June/July until at least September, and possibly even until December of each year.

While recruitment was strong at some sites (Grange and Brighton), it was negligible at others (Semaphore and Largs Bay). Given the two northern-most sites had the least recruitment, one possible reason for this spatial pattern could be the occurrence of a small-scale latitudinal gradient in recruitment success. However, previous work

in this system has suggested a strong temporal component to recruitment success (Collings et al. 2007), making it premature to discriminate spatial patterns from one year of sampling from natural temporal variation in recruitment. Alternately, poor recruitment at Semaphore and Largs Bay could be the result of seemingly faster degradation of hessian bags at these two sites, particularly the loss of the outer coarse hessian weave that appears a key structural trait of bags for facilitating recruitment (Wear et al. 2006). A third possible explanation could be a function of the relative abundance of the source population for *Amphibolis* recruits, with greater natural abundances of *Amphibolis* at Grange (~ 97 % cover) than at Semaphore (~ 54 % cover) (Wear et al. 2006). Other as yet untested models may include various environmental parameters that may influence *Amphibolis* recruits in this system, such as turbidity and resulting light availability, intensity of water movement (i.e. dislodgment of recruits), grazers, and nutrient-epiphyte loads.

A second critical component of rehabilitation efforts is the development and refinement of appropriate recruitment units. Wear et al. (2006) spent considerable time and effort testing the effectiveness of different materials and structures for the recruitment of *Amphibolis*, identifying the current design of sand-filled hessian bags with a coarse outer hessian weave as one of the most effective at attracting and retaining recruits over a 12 month period given biological (recruitment success), environmental (minimal impact) and economic requirements (cost-effectiveness). Experimentally varying the type of filling inside the hessian bags, as well as altering their layout, represents two tests to refine this design. The type of filling had no statistical effect on the recruitment of *Amphibolis*, although the mean density generally always ranked greater when bags were filled with sand instead of rubble (Fig. 1.5a). Likewise, the layout of bags had no effect on recruitment densities per unit area, regardless of whether bags were stacked vertically or laid flat, or whether multiple bags were lumped together or remained isolated. While many further tests can be done, it appears that the placement of a single isolated hessian bag filled with sand is as effective at facilitating recruitment of *Amphibolis* (if not more so) as any other arrangement of this standard unit that has been tested so far.

As noted in other studies (Wear et al. 2006; Collings et al. 2007), the degradation of bags appears a critical limiting step in the initial facilitation of recruitment and also subsequent retention of recruits. Coating bags with polymers aims to improve the longevity of hessian bags, and subsequently the recruitment and retention of *Amphibolis* to maximise its chances of becoming established in its own right. The

current experimental test of this coating procedure using organosilane and polyurethane coatings is at an early stage, and as would be expected even without polymer coating, there is presently no obvious differences in hessian quality among treatments. However, there already appears to be an effect on *Amphibolis* density, with bags coated with polyurethane exhibiting lower densities, possibly because the polyurethane was a slightly thicker coating than the organosilane, which may inhibit the attachment of *Amphibolis* through its grappling hook apparatus. It must be recognised, however, that such results are preliminary and should only be evaluated in the context of the entire period for which the experiment was designed (e.g. although recruitment is currently lower on polyurethane-coated bags, survival may ultimately be greatest because these bags may last the longest).

One notable feature of the long-term experiments presented here is the sharp decline in the height of *Amphibolis* recruits during April/May (see part b of Figs 1.3 – 1.6). Since this decline occurs prior to the June/July recruitment event, it cannot be readily explained by an influx of many small individuals reducing the average height of plants on each replicate bag. Although evidence is lacking, it is possible that the decline is driven by the increasing storm frequency at this time of year, with associated increases in wave energy and flow velocities imparting greater drag forces on larger individuals and causing their removal from bags. It should be noted that this decline was observed prior the first major recruitment event, and so densities were low, and plants that were lost were likely to have been relatively isolated. It is not clear if the same losses of tall plants would occur on units with a high density of recruits. Nevertheless, trials are currently underway involving the placement of semi-permanent video recording units at designated hessian bags to identify sources of *Amphibolis* loss.

Seagrass beds off the metropolitan coast of Adelaide have suffered historical losses (Seddon 2002) due to anthropogenic influences that increase coastal turbidity and nutrient loads (Bryars et al. 2006; Collings et al. 2006a; Collings et al. 2006b), but improvements in water management and quality have increased the likelihood of their natural recovery. While the loss of seagrass due to anthropogenic inputs can be rapid, natural recovery is often slow and is sometimes estimated to take hundreds of years (Kirkman & Kuo 1990; Bryars & Neverauskas 2008). To hasten this process and restore ecological function, habitat rehabilitation presents a valuable tool with strong chances of success provided adequate knowledge of the biology of the target species is available and appropriate methods are developed. In this context,

previous work has identified *Amphibolis* spp. as a prime candidate for rehabilitation off Adelaide, and work on the development and refinement of the hessian bag recruitment technique is continuing to provide the basis for a future large-scale rehabilitation project that has every chance of success.

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Chapter 2. Modelling the light environment of the Adelaide metropolitan coast

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2.1 INTRODUCTION

Habitat rehabilitation efforts face near-certain failure if poor environmental conditions, often the original cause of habitat loss, are not managed, monitored, and improved to promote the establishment, growth, and reproduction of the target species (Bell et al. 2008). Modelling key environmental variables can be a useful tool for habitat rehabilitation because locations of optimal environmental conditions for the target species can be identified *a priori*, allowing resource- and time-consuming rehabilitation efforts to concentrate on places with the greatest likelihood of success.

As autotrophs, seagrasses rely on adequate submarine illumination to support photosynthesis. Whilst the requirements differ between species, Duarte (1991) proposes a reasonably consistent average of 11 % of surface irradiance is required to support seagrass. However, Collings et al. (2006) estimated that *Posidonia* beds off the Adelaide coast were surviving at a depth of 18 m with approximately 4 % of surface light intensity. At depths greater than this (and consequently receiving less light) seagrasses ceased to exist.

The aim of this research was to provide a model that predicted the percentage of light transmitted to the seafloor for the metropolitan coast of Adelaide. This was achieved through the use of GIS techniques to produce a map of depth at a 25 m x 25 m resolution from a bathymetric map, and the collection of irradiance data from a series of underwater light meters situated off the coast of Adelaide at a variety of depths, from 1.7 m to 16 m, and sites from Brighton to Grange.

2.2 OUTLINE OF METHODOLOGY

Firstly, a GIS map was constructed, estimating depth for every point across the metropolitan coast of Adelaide, based on an existing bathymetric map. This was

used to determine the average depth (allowing for tides) of each of a series of light meters at numerous sites. As only some of these light meters recorded data for a full year, modelling was employed to estimate light intensity at those sites where a full year of data was unavailable.

By reference to measured surface light intensity, it was possible to calculate the average turbidity at each light meter on an annual basis. This is known as the vertical attenuation coefficient and it mathematically describes how much light is absorbed (and therefore does not reach the seafloor) for every metre of water. A very tight relationship between depth and attenuation coefficient was found, allowing the attenuation coefficient to be predicted for every point on the GIS depth map.

As the percentage of light transmitted to the seafloor is determined only by depth and the attenuation coefficient of the water, it was a simple extension to provide a model which calculated the percentage of surface light reaching the seafloor for all points on the GIS map.

The remainder of this work details each of the steps used to construct this model:

- 2.3 Development of depth map for the Adelaide coast
- 2.4 Field measurement of the submarine light climate
- 2.5 Modelling of submarine irradiance for entire year at all sites
- 2.6 Calculation of vertical attenuation coefficient
- 2.7 Relationship of vertical attenuation coefficient to depth
- 2.8 Extension of model to predict percentage light transmission

2.3 DEVELOPMENT OF DEPTH MAP FOR THE ADELAIDE COAST

Bathymetry was derived at a resolution of 25 m × 25 m using ArcView (ver 9.2), and based on the RAN hydrographic office AUS 780 map. The contour map of 0.5 fathoms resolution derived from the AUS 780 map was converted into a point feature file using XTools Pro software. Subsequently, the depths in fathoms were converted into metres by applying a conversion factor of 1.8288 to the dataset. The depth was further adjusted to a datum of mean sea level by adding 1.46 m to the dataset. The original contour dataset did not cover the depths along the shoreline. Hence, 54 new points were created to compliment the dataset along the shoreline represented in the AUS 780 map and were assigned depths of 0 m. Finally, the bathymetry of the study area was generated by implementing Kriging (ordinary) interpolation (ESRI 2001).

The final output of the depth mapping is shown in Figure 2.1. Depth shelves relatively uniformly, although more rapidly off the southern portion of the study area than in the north. Also, there is a moderately shallow region off Glenelg, with deeper water between it and the shore.

2.4 FIELD MEASUREMENT OF THE SUBMARINE LIGHT CLIMATE

A series of Odyssey photosynthetically active radiation (PAR) (400-700 nm) cosine type light meters (Dataflow Systems, New Zealand) were deployed off Grange at a range of depths on March 10th 2005, recording average light intensity for each half hour period. Each of these was attached to the top of a star picket with cable ties such that it sat 60 cm above the sand substratum to approximate the canopy height of an *Amphibolis* / *Posidonia* seagrass meadow. Meters were located at distances approximately 0.5, 1, 2.5 and 3.5 km from the shore (Figure 2.2). These are referred to as the shallow, medium-shallow, medium-deep and deep sites. The shallow site was inshore of the nearshore seagrass edge, in the area from which seagrass has been lost. The medium-shallow site was just within the seagrass zone, and the deep site is just within the seaward (deep) edge of the seagrass zone. The medium-deep site was approximately 2/3 of the way to this deeper edge. Meters were exchanged on an approximately fortnightly basis in order to ensure that light readings were not affected by algal growth on the sensors. Meters at the Grange sites were maintained until March 11th 2006, allowing an almost continuous record over the course of an entire year. There were a few days where readings were not obtained, and values had to be estimated from modelling. The methodology used is described later.

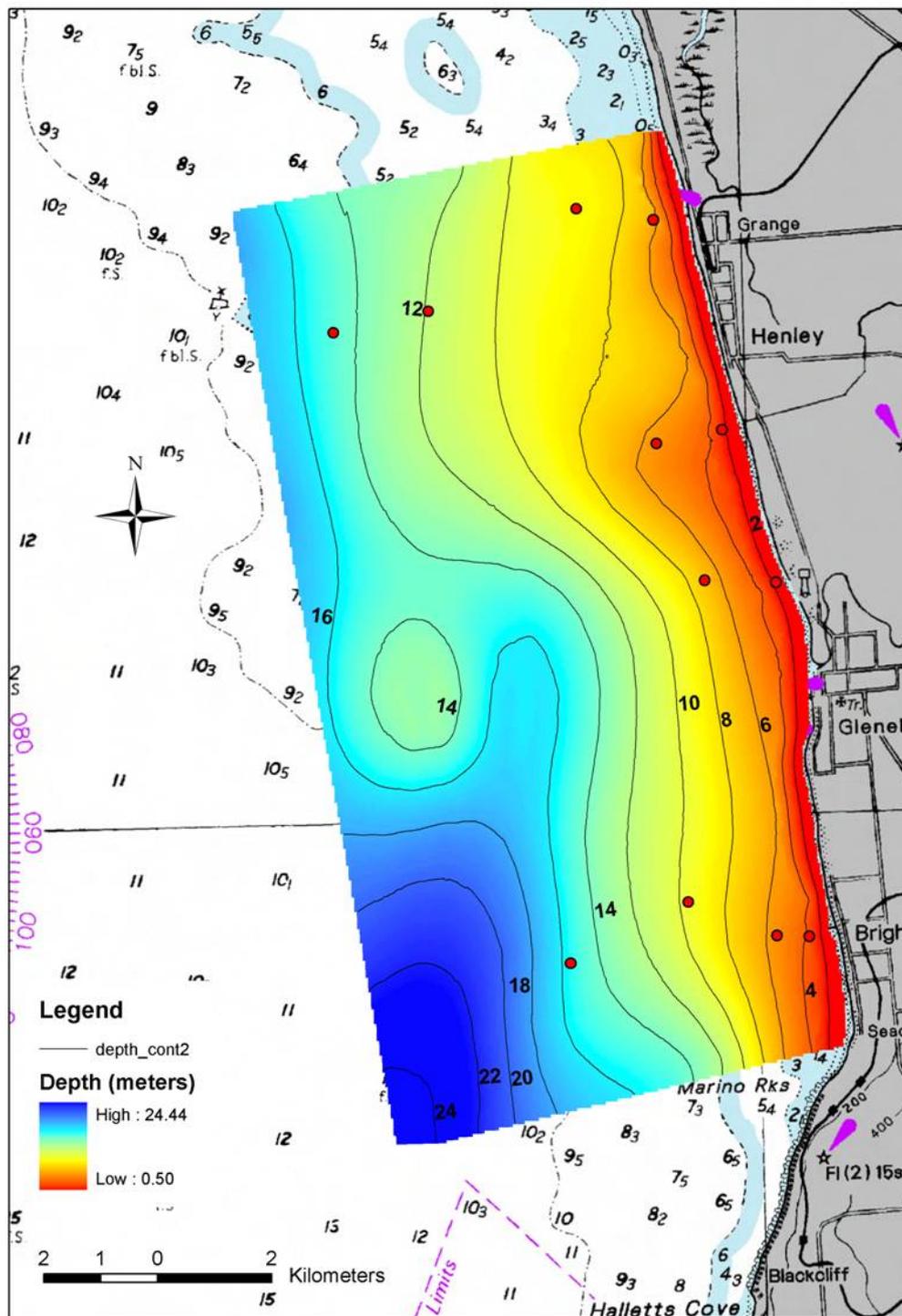


Figure 2.1. Depth map of the Adelaide coast with a GIS layer (in colour) calculated from interpolation of the bathymetry of the original map. Note that the bathymetry contours provided on the coloured section are expressed in metres whilst the background bathymetry is in fathoms. Adjustment to mean sea level has also been applied for the GIS layer. The positions of light metres are indicated with red circles.

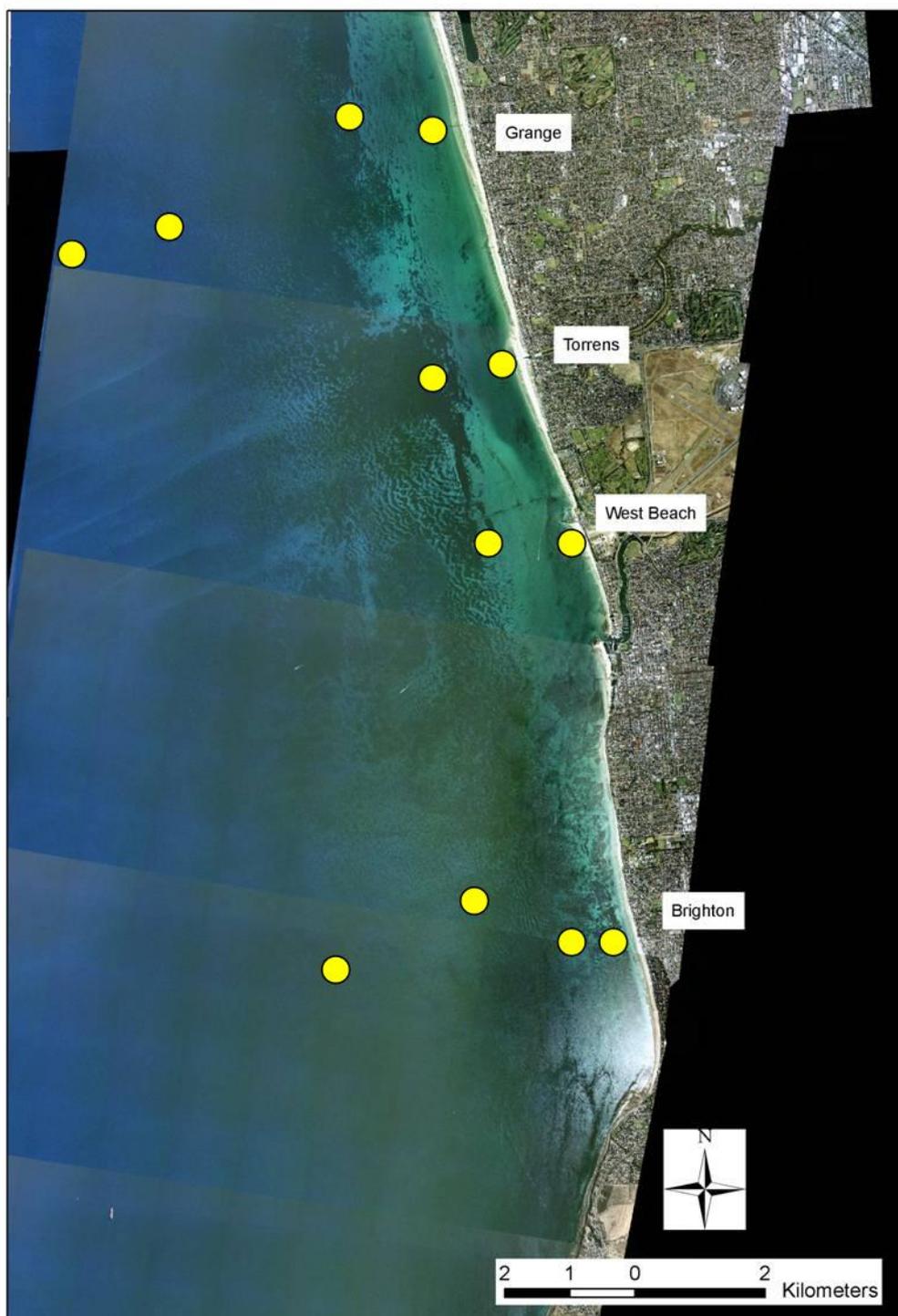


Figure 2.2. Aerial photograph showing the location of offshore submerged light meters (yellow circles) off Brighton, West Beach, the Torrens River and Grange. Black areas were not available from aerial photographs.

In addition to data from the four Grange sites over the entire year, PAR levels were also recorded at a series of eight additional secondary sites over a restricted timeframe. These sites were:

- Brighton at shallow, medium-shallow, medium-deep and deep sites
- West Beach at shallow and medium-shallow depths
- Offshore of the Torrens River Outlet at shallow and medium-shallow depths

The depth of each meter in relation to MSL (see Table 2.1), was determined from the depth map discussed above.

In addition to being restricted to the period 18/5/2005 to 11/3/2006, there were also several absences at various sites caused by lost or damaged meters at various times and for different durations. Whilst the Grange sites had data for 365 days, there were 151 days common to all sites.

Table 2.1. Depths of each light meter expressed in metres below mean sea level (MSL).

	Shallow	Med-Shallow	Med-Deep	Deep
Grange	6.3	8.8	11.9	14.8
Torrens Outlet	2.5	5.6		
West Beach	1.7	7.1		
Brighton	3.5	5.4	9.6	15.6

2.5 MODELLING OF SUBMARINE IRRADIANCE FOR THE ENTIRE YEAR AT ALL SITES

2.5.1 Grange

Half-hourly readings of average PAR intensity were provided by the loggers. These were summed and multiplied by 1800 to adjust for measurements expressed in $\mu\text{mol photons m}^{-2}$ per second rather than per half hour. This provided readings for daily PAR dose (in $\text{mol photons m}^{-2}$ per day).

On occasion, because of problems with the light logging units, it was necessary to estimate appropriate values. For example, when light loggers were changed over, there was a period of an hour where the data were likely inaccurate as during this time both the new and replaced light metres may be on the boat deck, receiving full sun. For these periods, the values were modelled using the following formula:

$$\text{Irradiance}_{d,t} = \text{Irradiance}_{d-1,t} \times (\text{Irradiance}_{d,t-1} + \text{Irradiance}_{d,t+1}) / (\text{Irradiance}_{d-1,t-1} + \text{Irradiance}_{d-1,t+1}) \quad (2.1)$$

where d indicates the day in question and d-1 indicates the previous day

t= the time requiring a modelled value; t-1 indicates the previous hour, t+1 the following hour

In essence, this creates a value based on the value at the same time on the previous day modified by the ratio of irradiance on the day in question to the previous day. Calculation of this ratio is based only on the hour either side of the time in question.

2.5.2 Modelling the days missing using the relationships to Grange

Although each site had more recording days, there were a total of 151 days on which recording was carried out at all 12 sites. To characterise the among-site relationship in the amount of PAR received, the total irradiance over the 151 common days was calculated by summing the daily totals. Average daily PAR over this period is indicated by Figure 2.3. Subsequently each site was described in terms of its relationship to the Grange site of the same approximate depth. For example Brighton (shallow) had 134 % of the light obtained by Grange (shallow), and Brighton (medium-shallow) had 138 % of the Grange (medium-shallow) site. These comparisons are shown in Table 2.2.

As an entire year of daily irradiances was measured for the Grange sites, it was possible to model the missing days at other sites on the basis of the relationships described in Table 2.2 and the light received at the appropriate Grange site on those days. For example, if there was no reading available for Brighton (shallow) but Grange (shallow) had a total for the day of 1000 mol photons m⁻², then the amount assumed for Brighton (shallow) was 1000 x 1.34 (= 1340 mol photons m⁻²). This modelling was done at all 8 sites for each day where a reading was not obtained at all sites (i.e. for 214 days). Note that seasonal variation is incorporated in this model because real seasonal variation is recorded in the Grange dataset and therefore translated into the other sites. What is assumed here is that the relationship between the sites is maintained between the 151 days where measurement took place and the 214 days when it did not.

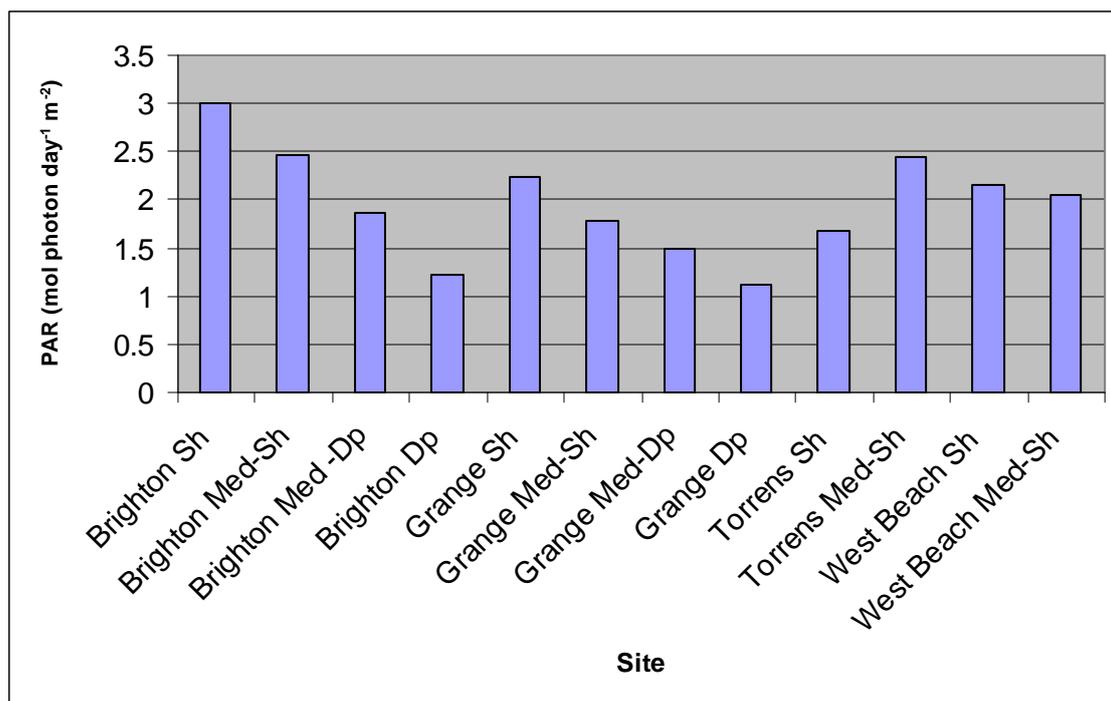


Figure 2.3. Average Daily PAR calculated across the 151 days in common to all sites.

Table 2.2. Ratios of average daily PAR (calculated across a year) between sites. The critical ratios for modelling PAR for missing days are between each site and the Grange equivalent of the same depth. Site codes indicate the location with a letter: B = Brighton, G = Grange, T = Torrens, WB = West Beach, and a number indicating the depth: 1 = shallow, 2 = med-shallow, 3 = med-deep, 4 = deep.

	B1	B2	B3	B4	G1	G2	G3	G4	T1	T2	WB1	WB2
Daily PAR (mol photons day ⁻¹ m ⁻²)	2.99	2.46	1.87	1.23	2.23	1.78	1.48	1.12	1.67	2.44	2.16	2.05
as proportion of Grange Deep				1.10				1.00				
as proportion of Grange Med -Deep			1.26					1.00				
as proportion of Grange Med -Shallow		1.38				1.00			1.37			1.15
as proportion of Grange Shallow	1.34				1.00				0.75		0.97	

2.6 CALCULATION OF VERTICAL ATTENUATION COEFFICIENT

The vertical attenuation coefficient is a measure of the turbidity of the water and is an indication of the proportion of downwelling light absorbed by the water column for each metre of water. It is described by the equation (adapted from Lund-Hansen 2004):

$$K_d = -\ln(I_D/I_S)/D \tag{2.2}$$

Where; K_d = Vertical Attenuation Coefficient,
 I_D = the yearly total of PAR at the meter on the seafloor and

I_S = the yearly total of PAR at the surface (corrected for reflection) and
D = the depth in metres.

While the field measurements from light meters and subsequent modelling provide data for I_D , and depth is provided from the bathymetric map, measurements of surface light intensity are required in order to calculate K_d at each site. This was provided from a surface light meter situated at West Beach and adjusted to allow for surface reflection throughout the day (for full details see Collings et al. 2006). A full year of almost uninterrupted surface light readings was collected.

Where surface light readings were unavailable (approximately 7 % of readings), they were modelled from half-hour global insolation data recorded at Adelaide airport by the Bureau of Meteorology. By comparing daily total insolation as recorded by our loggers with that obtained from Adelaide airport over all periods where both were available, it was possible to calculate the ratio between the two for each month. This ratio was then applied to the airport data in order to model half hourly insolation as it would be recorded by our loggers. To check the validity of the approach, a month where data were available from both sources was used to produce a modelled light field. When compared to the actual data, the model produced an excellent fit (Figure 2.4). The r^2 value (Sum of Squares_{model}/Sum of Squares_{actual}) was 0.98, indicating that 98 % of the variation in the real data was explained by the model. On this basis, it was concluded that the modelled data would be appropriate. Vertical attenuation coefficients on the basis of the yearly light budget for each site were then calculated as described by equation 2.2, and are detailed in Table 2.3.

It is worth noting that these figures are not identical to those of Collings et al. (2006) because that study utilised depth measurements obtained in the field, whilst the current study applied depths obtained from the bathymetric charts. This was necessary to achieve consistency in the final output where a chart of percentage light transmission was produced based on the mapped depth (see section 2.8).

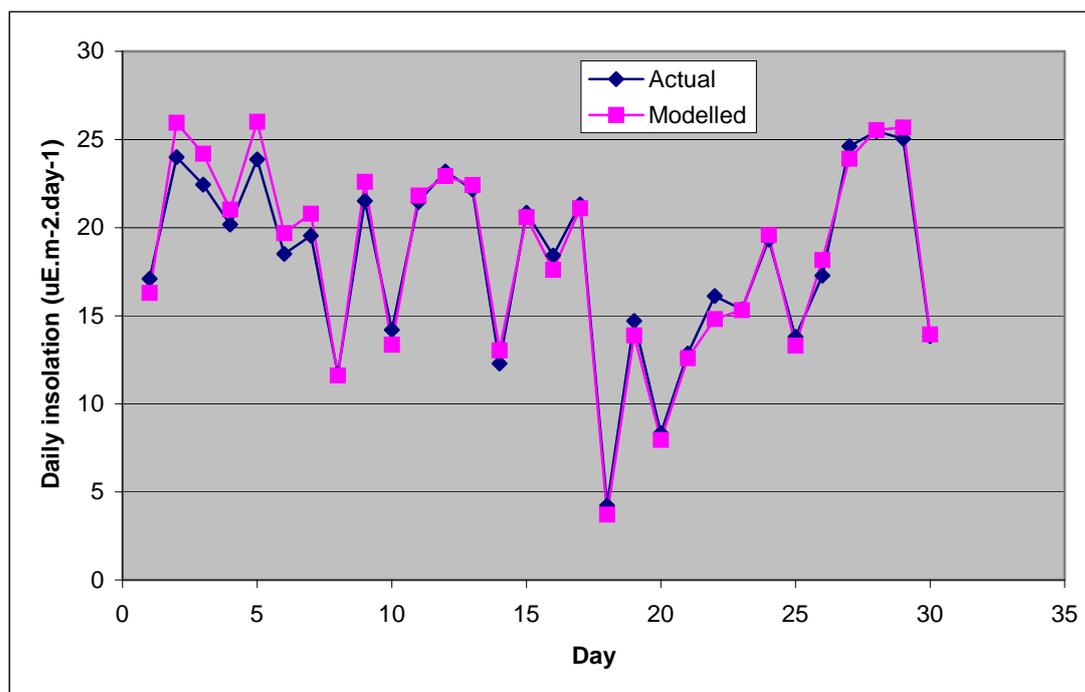


Figure 2.4: Fit of the modelled data against real data to test whether modelled data were appropriate for use where actual data were not available. r^2 was 0.98.

Table 2.3. Vertical attenuation coefficients of each site, based on recorded and modelled annual light budget and depths from mean sea level as described by the earlier section on bathymetric mapping.

	Shallow	Med-Shallow	Med-Deep	Deep
Grange	0.371	0.284	0.235	0.219
Torrens Outlet	0.875	0.364		
West Beach	1.454	0.390		
Brighton	0.584	0.400	0.266	0.201

2.7 RELATIONSHIP OF VERTICAL ATTENUATION COEFFICIENT TO DEPTH

Turbidity in Gulf St Vincent is strongly related to depth in nearshore regions (Phillips and Sholz 1982) where seagrasses are found. Therefore it was assumed that a relationship between depth and the attenuation coefficient could be determined which would allow depth to be used as a proxy for turbidity, and by extension for surface irradiance transmission.

The relationship between attenuation coefficient and depth was not linear. However, by applying a natural log (ln) transformation to the depth, a power curve could be fitted to the relationship using MS Excel (Figure 2.5).

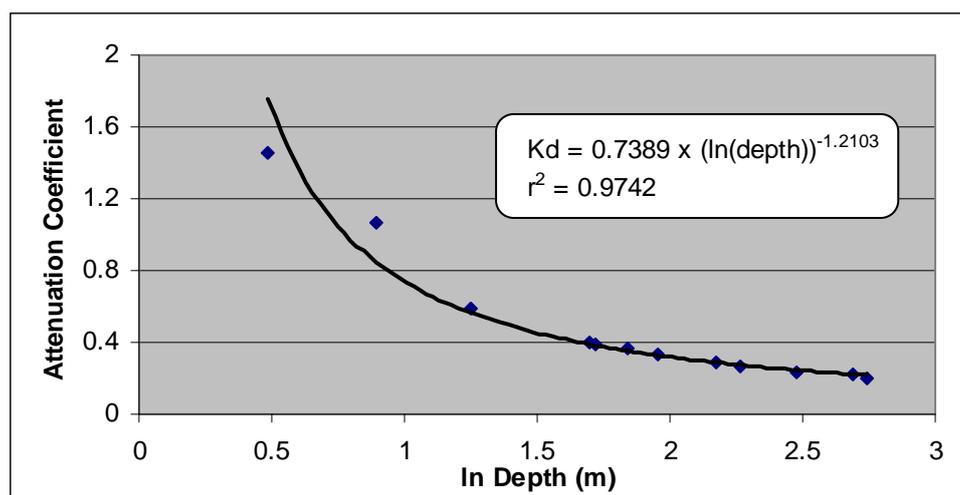


Figure 2.5. Vertical attenuation coefficient as a function of ln transformed depth. A power curve has been fitted which explains 97.4% of the variance.

The best fit was achieved using the following model:

$$K_d = 0.7389 \times (\ln(\text{depth}))^{-1.2103} \quad (2.3)$$

This model produced an extremely good fit to the data, as evidenced by an r^2 value of 0.9742. This would indicate that depth is an extremely good predictor of turbidity.

Figure 2.6 illustrates the vertical attenuation coefficient for Adelaide's coastal waters. It demonstrates greatest turbidity close to shore and greatest clarity offshore, which is unsurprising given that the coefficient was calculated from depth which obviously has a strong relationship to distance from shore.

It had been suggested that distance from shore might be just as important a predictor as land-based discharges that are entrapped in the nearshore region (Fox et al. 2007). However, the best model that we could produce using distance from the shore explained only 86 % of the attenuation data, which is a worse fit than that achieved using depth as a predictor. Furthermore, much of the 86 % is likely to be due to the correlated effect of depth, which is strongly related to distance from shore.

Similarly it was considered that location along the coast (as opposed to distance from the coast) might be important. However, with only 4 general sites studied along the coast, and the potential for point source input, it was not considered suitable to use this data to assess the effect of site.

Given the extremely good fit provided by the use of depth alone as a predictor (97.4 %), it was used as a simple predictor without resorting to the use of other additional factors.

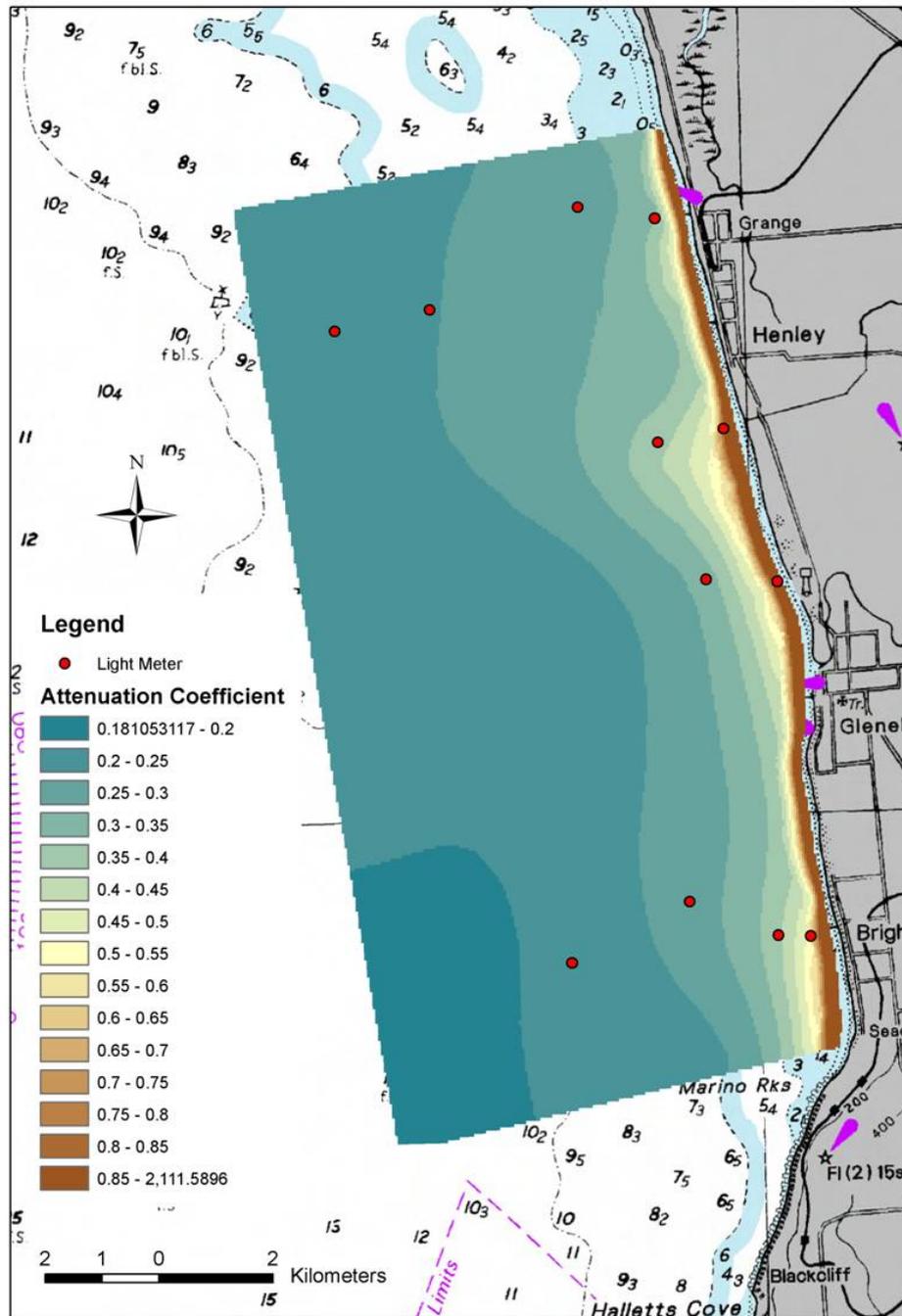


Figure 2.6. Turbidity of Adelaide’s coastal waters as described by the vertical attenuation coefficient. Colour indicates clarity, with brown being very turbid and dark blue clear.

2.8 EXTENSION OF MODEL TO PREDICT PERCENTAGE LIGHT TRANSMISSION

The proportion of surface light reaching the seafloor is calculated using the equation:

$$I_D = I_s \times e^{-K_d \cdot D} \quad (2.4)$$

Where; K_d = Linear Attenuation Coefficient,
 I_D = the yearly total of PAR at the meter on the seafloor and
 I_s = the yearly total of PAR at the surface (corrected for reflection) and
 D = the depth in metres.

If 100 % is substituted for I_s , then the calculated value for I_D will represent the percentage of surface light reaching the seafloor.

Furthermore, as K_d has been accurately modelled on the basis of depth, it can be replaced in the equation by the model described in section 2.7, producing the equation:

$$I_D = 100\% \cdot e^{-(\text{depth} \cdot (0.7389 \cdot (\ln(\text{depth}))^{-1.2103}))} \quad (2.5)$$

This calculation was made for every unit on the GIS map to produce a map of the percentage of surface irradiance reaching the seafloor across the Adelaide metropolitan coast, from Brighton in the south to Grange in the north, and from the low water mark to a depth of approximately 18 m (Figure 2.7). It is evident that the percentage of light reaching the seafloor is a close reflection of the depth map (Figure 2.1.). This is unsurprising given that the calculation of percentage transmission relies only on knowledge of depth. However, given the very strong relationship between vertical attenuation coefficient and depth, where more than 97% of the variability in attenuation coefficient could be explained, this is not an unreasonably simplistic model. It is, however, worth reiterating that the model is not a simple linear relationship between depth and percentage light transmission. Indeed the relationship is not consistently negative. Figure 2.8 graphically represents the model described by equation 2.5. It is evident from this model that in shallower regions, an increase in depth is actually associated with an increase in percentage light transmission. According to the model, transmission increases to a maximum of approximately 14 % at a depth of approximately 3.5 m. The validity of this result is

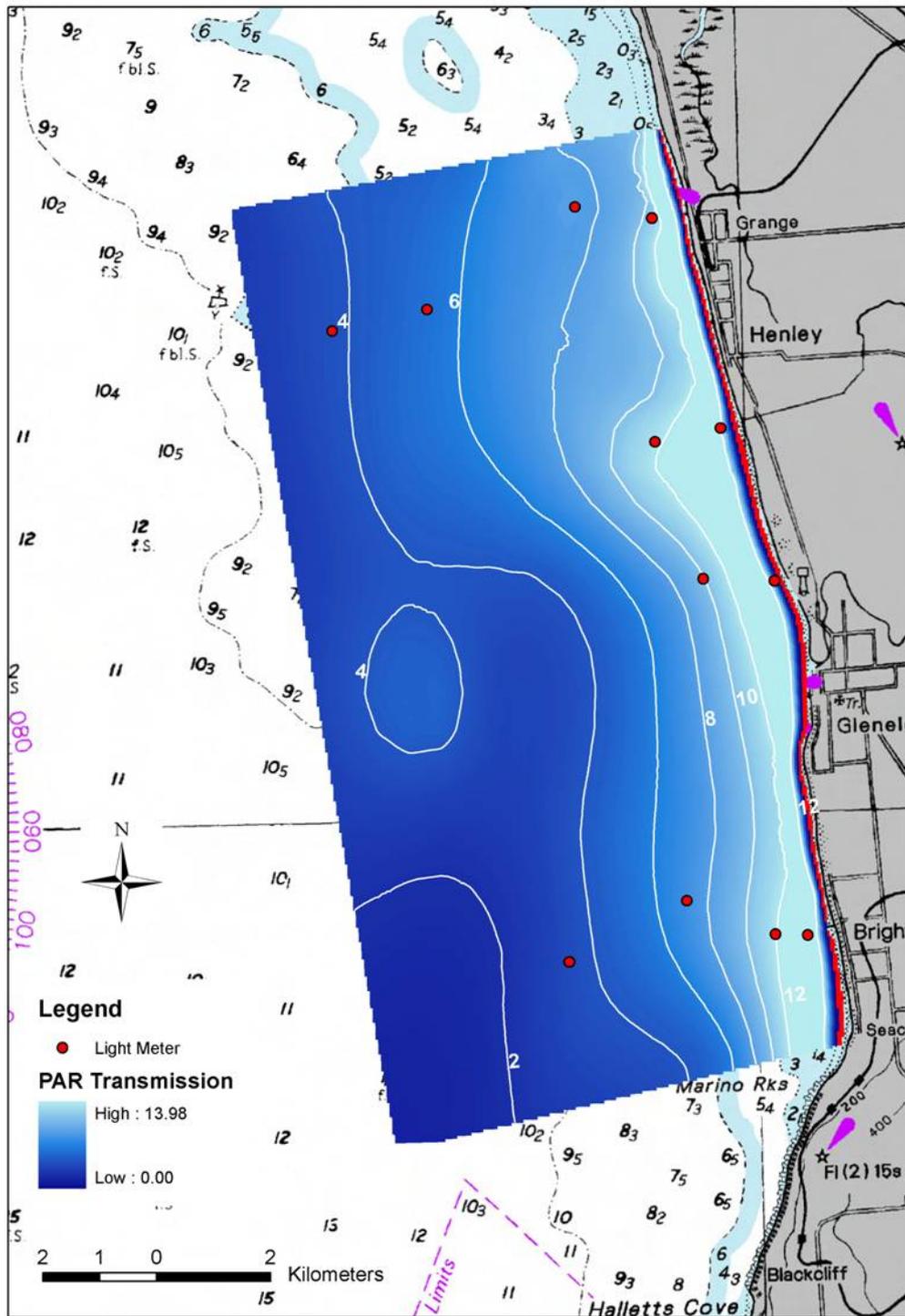


Figure 2.7. Percent transmission of surface light (PAR) to the seafloor for Adelaide’s coastal waters. White contour lines are overlaid to assist interpretation and labelled with the percentage of light reaching the seafloor.

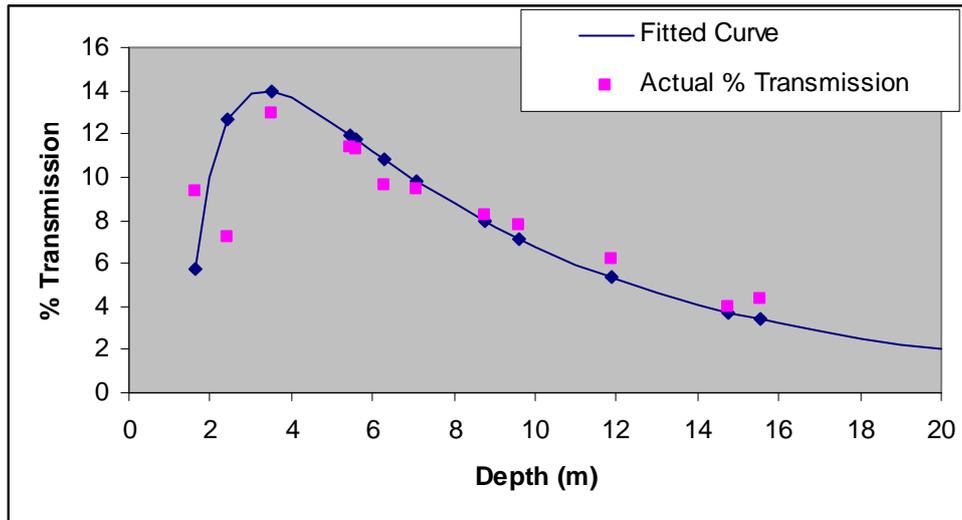


Figure 2.8. Graphical representation of the relationship between surface light transmission and depth as modelled by equation 2.5. The blue line represents the modelled relationship, while the pink squares represent the actual percentage of surface light transmitted to the seafloor at each of the light meters.

untested as only two light metres existed in this region. Furthermore, these two points represented by far the greatest discrepancy between modelled and actual transmission. While these two sites did demonstrate lower percentage light transmission than many deeper sites, there may be other explanations such as the close proximity of the Barcoo and Torrens outlets that may have skewed estimates. Further field investigations focussed on the shallower regions are necessary to confirm this finding.

For the purposes of identifying areas where lack of light may influence seagrass survival, it is worth noting that seagrass survives to approximately 18 m, and it is assumed that this represents the effect of light limitation. Thus, as the percentage of surface light reaching the seafloor tends toward the values demonstrated at 18 m, the environment is tending toward light limitation for seagrasses. It must be recognized that this is a necessarily simplistic representation as it does not take into account the effect of variability in light regime on scales of less than a year which may be important, nor does it incorporate changes in photophysiology which might occur based on shorter time intervals, which may allow plants at 18 m to be more efficient in their use of light than shallower plants. It simply models the annual light budget. Ultimately, the survival of seagrasses depends not on light levels, but upon productivity. Greater understanding of the physiology of the plants of the Adelaide

coast is required before a useful productivity model can be produced. Collings et al. (2006) provide a more detailed discussion of this matter.

2.9 REFERENCES

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