SEAGRASS HABITAT MODEL
Adelaide's Coastal Waters

Literature review of habitat requirements of seagrasses in Adelaide's coastal waters

- Author: Paul L.A. Erftemeijer
- Rev 2
- 27 February 2014

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1. Introduction

Since the 1940s, some 5000 ha of seagrass meadows have been lost from Adelaide's coastal waters. In response to this, the Adelaide Coastal Waters Study was initiated (2003–2005; see Fox et al., 2007), the results of which attributed this considerable decline to high nutrient loads that have stimulated phytoplankton and epiphyte growth and as such decreased the availability of light for the seagrasses. High suspended sediment concentrations from stormwater drains were also considered to have played a role in the seagrass decline, while sediment instability (caused by the loss of seagrass) may hamper seagrass recovery.

In response to these studies, the Adelaide Coastal Water Quality Improvement Program (ACWQIP) aims at a reduction in nitrogen loads of 75% of 2003 levels and a reduction in sediment loads of 50%, as well as an unquantified reduction of coloured dissolved organic matter (CDOM) for 2020-2030. This has evident consequences for SA Water operations. By 2013, a substantial reduction in effluents from waste water treatment plants (WWTP) has already been realized, but further reductions require considerable investments. Moreover, the population of Adelaide is expected to grow by up to 45-50% between 2006 and 2036, resulting in higher volumes of wastewater to treat and a larger drained urbanized area.

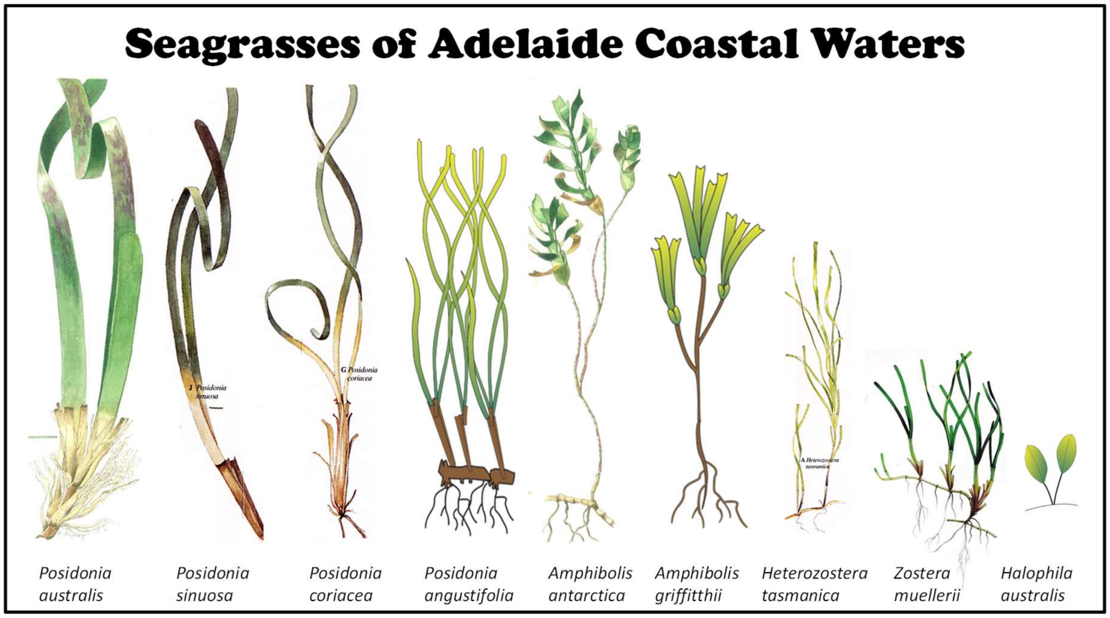
To overcome this situation, SA Water aims at developing targeted coastal water modelling capabilities that could assist SA Water in answering the following questions: [1] what are the tipping points of the system for seagrass deterioration and potential recovery? [2] what is the role of nutrients in relation to other stressors for seagrass deterioration and potential recovery? [3] how do the temporal (seasonal) and/or the spatial distribution (location) of discharges affect the conditions for seagrass growth and potential recovery in the Adelaide coastal waters?

As a first step in this process, SA Water has commissioned Deltares and its subcontractor SKM to develop an Adelaide Coastal Waters Pilot Hydrodynamic-Sediment-Biogeochemical Model. This pilot model is based on currently available data and knowledge about system functioning, and should serve as a proof of concept. Part of this pilot phase is to model the habitat suitability for seagrasses in the study area.

The present report presents a literature review of environmental parameters affecting seagrasses in Adelaide Coastal Waters from which species-specific knowledge rules are derived for these parameters which will be used as input in the Seagrass Habitat Suitability Model for Adelaide Coastal Waters.

2. Seagrasses of Adelaide Coastal Waters

There are an estimated 15,000 km^2 of seagrass beds in southern Australia (Greenwood and Gum, 1986) with 5,000 km^2 in South Australia; 3,700 km^2 in Spencer Gulf and 1,530 km^2 in Gulf St. Vincent (Shepherd and Robertson, 1989). Seagrasses in South Australian waters have suffered significant declines, including the loss of more than 5,000 hectares in the Adelaide Coastal Waters due to anthropogenic causes (Westphalen et al., 2004) and a die-back of 12,717 hectares in Spencer Gulf due to natural causes (Seddon et al., 2000).



Notes: *Heterozostera tasmanica = Z. tasmanica; Zostera muellerii = Z. capricornii*

Figure 1. Seagrass species in Adelaide coastal waters.(drawings from: Integration and Application Network)

Adelaide's Coastal Waters support nine seagrass species (**Figure 1**): *Posidonia australis, Posidonia sinuosa, Posidonia coriacea, Posidonia angustifolia, Amphibolis antarctica, Amphibolis griffithii, Heterozostera tasmanica* (=*Zostera tasmanica*), *Zostera muellerii* (= *Zostera capricornii* = *Zostera mucronata*) and *Halophila australis*. In addition, there are three additional species of submerged angiosperms (i.e. *Lepilaena marina, Ruppia megacarpa* and *Ruppia tuberosa*), which are not considered further for this review, as they comprise species that primarily occur in saltmarshes and hypersaline lakes up to ten times the salinity of seawater (Robertson, 1984), are often not considered true seagrasses and were reportedly not among the species affected by the widespread seagrass losses in SA. In terms of biogeography, the nine seagrass species in SA waters have affinities ranging from cool temperate to warm temperate (Shepherd and Robertson, 1989). Almost all are perennial and flower in spring and summer, grow across various depth ranges from the intertidal to 40 metres and vary in size from 5 cm to 120 cm in length. This diversity encompasses a wide array of morphologies and life histories and thus a range of responses to disturbance (Duarte et al., 1997).

The dominant seagrass species in South Australian waters are the meadow-forming *Posidonia sinuosa, P. angustifolia* and *P. australis. Posidonia australis* is generally the climax species in more sheltered areas, while *P. angustifolia and P. sinuosa* dominate areas that are more exposed. *Posidonia coriacea* is never abundant and generally occurs as small isolated stands or as a fringe community (Shepherd and Robertson, 1989). *Amphibolis antarctica* and *A. griffithii* occur as a fringe community on the edge of blowouts where colonisation occurs, on thin veneers of mobile sediments or in mixed stands with each other or with species of *Posidonia*. *Amphibolis griffithii* tends to occur at greater depths (10-15 m) and in stronger currents than *A. antarctica*, which rarely occurs below 12 m. *Heterozostera tasmanica* is nearly ubiquitous, forming a sublitoral fringe above the *Posidonia* meadows. *Halophila australis* is widespread but mostly sparse and occurs from the intertidal to deeper waters up to 35 m in gulfs and bays. *Zostera muellerii* is the most abundant seagrass on the intertidal mudflats and estuarine habitats of the South Australian gulfs.

Seagrass mapping data and analysis during the Adelaide Coastal Waters Study indicate that more than 5,000 hectares of seagrass were lost from Adelaide’s coastal waters since the early 1970s. These losses have mainly occurred in a 1 – 2 km wide strip, parallel to the shore of Holdfast Bay (Outer Harbour to Brighton), with smaller areas located around the Port Adelaide sludge outfall (operational from 1978 – 1993) and at a dredge spoil-dumping ground off Outer Harbour. Seagrass loss has also been recorded for areas further north (St Kilda to Port Gawler) as well as in deeper water off Point Malcolm. The spatial and temporal pattern of seagrass losses adjacent to Adelaide broadly correlates with the pattern of coastal development and anthropogenic inputs into coastal waters (Westphalen et al., 2004).

There are differences in the rate of loss between species, with *Amphibolis antarctica* appearing to be more sensitive to declines in water quality than *Posidonia sinuosa* or *P. angustifolia*, possibly through greater sensitivity to high epiphyte loads or even nutrient toxicity (see below). More recently, the rate of decline has decreased, possibly due to the decommissioning of sludge outfalls at Glenelg and Port Adelaide, and recent improvements in wastewater treatment and catchment management (Westphalen et al., 2004; Bryars and Rowling, 2009).

3. Habitat Suitability Model

3.1. Parameters affecting seagrass

Seagrasses are the only angiosperms that are adapted to a marine submerged existence. Basic requirements for growth (e.g. light, nutrients) are similar for terrestrial angiosperms and seagrasses alike (Hemminga and Duarte, 2000). Life in the marine realm, however, implies exposure to environmental conditions that are considerably different in many respects from those in terrestrial habitats, imposing constraints on the availability of some essential resources, or calling for specific adaptations to acquire others (Hemminga and Duarte, 2000).

In general, the suitability of a location as a habitat for a certain species depends on the environmental conditions at that location. For example, the suitability of a location for certain species of seagrass depends upon temperature (**Figure 2**). Between a certain lower and upper threshold, the temperature is optimal for the growth of this species and the suitability of this location for this seagrass species with respect to temperature is 1 (equivalent to 100%, defined as optimal). When the temperature exceeds the upper threshold or becomes lower than the lower threshold, the suitability of the location for the growth of this seagrass species will become less than 1. When the stress due to the temperature becomes too high (i.e. at extreme high and low temperatures), the suitability index will become 0 and this species of seagrass will no longer be present at these conditions. Note that temperature is used here just as an example to illustrate a generality.

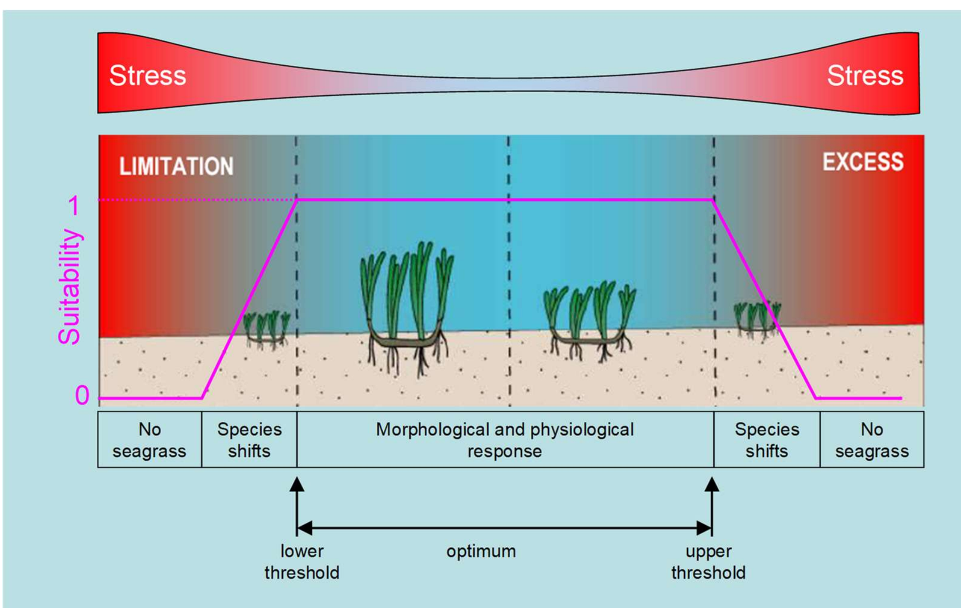


Figure 2. Schematic overview of the response of seagrass to an environmental factor.

For some parameters there is no obvious upper threshold (e.g. light availability – although in some cases seagrasses growing in the upper intertidal can be stressed by photoinhibition) and seagrass growth is only limited by low levels of these parameters. For some other parameters, there is no lower threshold (e.g. wave exposure), when seagrass growth is only limited by high levels of these parameters.

Seagrass growth and survival is determined by a wide range of environmental parameters and anthropogenic disturbances. It may therefore seem best to take as many parameters into consideration as possible in the habitat suitability model, in order to produce the most accurate predictive results. In our experience, however, this is often not the case. Grech and Coles (2010) developed an ecosystem-scale predictive model of coastal seagrass distribution for the Great Barrier Reef (GBR) World Heritage Area based on eight environmental drivers and found that at the scale of the entire coastal GBR, two main drivers, i.e. tidal range and relative wave exposure, determined most of the presence/absence of seagrasses. Similarly, Van der Heide et al. (2009) found that presence or absence of two temperate seagrass species (Zostera marina and Zostera noltii) at 84 Western European locations could be reliably predicted by using only two easy-to-measure variables - light availability and sediment porewater redox – which correctly predicted 77-86% of all observations. Furthermore, modelling results for predicting habitat suitability not only depend on the number of parameters considered for use as input, but their reliability also depends on the accuracy of the spatial information of the input files (as maps) and the degree of uncertainty in the information used to establish the knowledge rules.

This chapter summarizes the available ecological information for the nine seagrass species occurring in Adelaide coastal waters, with respect to their optimum and critical thresholds (minimum and maximum tolerated) for some of the most critical environmental parameters that determine seagrass growth and survival. The focus is specifically on those environmental parameters for which sufficient scientific information exists and all information here has been derived from scientific literature following an intensive literature study. These literature values are subsequently used to define tolerance thresholds as input into the habitat suitability model.

3.1.1. Light

Light is one of the key environmental resources imperative for the growth and survival of seagrasses (Hemminga and Duarte, 2000). The degree of water transparency (which determines the depth-penetration of photosynthetically active radiation of sunlight) is the primary factor determining the maximum depth at which seagrasses can occur. Reduction in light due to turbidity has been identified as a major cause of the loss of seagrasses worldwide (Shepherd et al., 1989; Green and Short, 2003). The amount of light that reaches a seagrass leaf is determined by the natural water colour, the concentration of suspended solids (incl. fine sediment particles and dead organic matter) and phytoplankton in the water, and the epiphyte cover of the leaf (**Figure 3**).

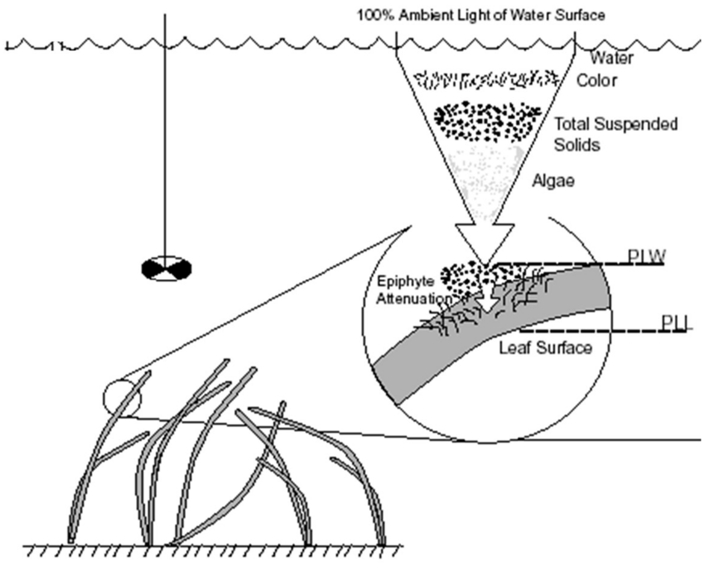


Figure 3. Diagram describing the factors influencing the amount of light reaching a seagrass leaf (Batiuk et al., 2000).

There are various reports of sublethal and lethal effects on seagrass meadows due to prolonged exposure to high turbidity (Caldwell, 1985; Gaby et al., 1986; Onuf, 1994; Gordon et al., 1994; Chesire et al., 2002). Laboratory experiments have shown that some seagrasses can survive in light intensities below their minimum requirements for periods ranging from 4 weeks to several months (Backman and Barilotti, 1976; Bulthuis, 1983; Gordon et al., 1994; Czerny and Dunton, 1995; Longstaff et al., 1999).

There are a considerable range of values reported in the literature for the minimum light requirements of seagrasses, both between different seagrass species, as well as within a single seagrass species (Erftemeijer and Lewis, 2006). The variation in minimum light requirements reported in literature is in part caused by differences in the methodologies used to derive these values. These range from physiological studies of photosynthesis/irradiance relationships, field observations of the maximum depth of seagrass colonization and experimental manipulation of light levels during growth studies, to statistical models (Batiuk et al., 2000). The various studies and methods further differ in the degree to which attenuation by epiphyte cover of seagrass leaves, natural water colour, seasonal variation, above/below-ground biomass ratios, environmental factors other than light and sublethal effects have been taken into account (Erftemeijer and Lewis, 2006).

Amphibolis antarctica

The minimum light requirements of *Amphibolis antarctica* have been studied at sites in Victoria and South Australia. The values reported for the minimum light requirements of this species vary between 5 and 24.7% of Surface Irradiance (SI) (Duarte, 1991; Dennison et al., 1993; Bryars and Collins, 2008; Bryars and Rowling, 2009). Bryars and Rowling (2009) reported a maximum depth limit for most *Amphibolis antarctica* in Adelaide's coastal waters to be in the order of 12 m. Bryars and Collins (2008) reported 100% survival of *Amphibolis antarctica* when shaded to 0% SI for 6 weeks, but a loss of nearly all epiphytes.

Amphibolis griffithii

The minimum light requirements of *Amphibolis griffitthii* have been studied in Western Australia and reported to be in the order of 20% of Surface Irradiance (SI) (McMahon and Lavery, 2008; McMahon et al., 2011). Plants suffered significant stress if shading below 19%SI was sustained. Plants lost 72% of their leaf biomass if shaded to 5-18%SI for three months but showed rapid recovery after removal of the shading. Plants lost 89-100% of their leaf biomass if shaded to 6-9%SI for 6-9 months and showed no signs of recovery after removal of the shading (McMahon and Lavery, 2008; McMahon et al., 2011).

Posidonia australis

The minimum light requirements of *Posidonia australis* have been studied in New South Wales and reported to be in the order of 10% of Surface Irradiance (SI), showing significant mortality if shaded to <10%SI for more than three months (Fitzpatrick and Kirkman, 1995). Masini et al. (1995) reported that *Posidonia australis* plants in Western Australia required much more light to maintain a positive carbon balance than *Posidonia sinuosa* or *Amphibolis griffitthii*.

Posidonia sinuosa

The minimum light requirements of *Posidonia sinuosa* have been exhaustively studied in a range of locations and environments in Western and South Australia. The values for the minimum light requirements of this species, as reported in literature, vary between 4 and 24.7% of Surface Irradiance (SI) (see Table 1 for overview). DEP (1996) reported the minimum light requirements of *Posidonia sinuosa* to vary seasonally between 5 and 12%SI. Collier et al. (2009) noted a 82-91% shoot loss in this species after 105 days when shaded to 4-5%SI. Gordon et al. (1994) reported reduced growth for this species if shaded to less than 20%SI after one year and an onset of mortality after two years if shaded to less than 10%SI. Similarly, Gordon et al. (1994) recorded the loss of 30-55% of shoots at 80-99% shading after 104 days. They noted plants of this species surviving for 24 months at 12%SI, after which the meadow collapsed due to high plant mortality. Collings et al. (2006) reported a healthy surviving meadow of this species at 18 m water depth at a site in South Australia where ambient light availability was ~4% of SI.

Table 1. Minimum light requirements for *Posidonia sinuosa*, as reported in literature.

Seagrass species	%SI	Location	Reference
Posidonia sinuosa	4	SA	Collings et al. (2006)
Posidonia sinuosa	7.8	WA	DEP (1996)
Posidonia sinuosa	8.5	WA	Collier (2006) PhD thesis
Posidonia sinuosa	10	WA	Masini et al. (1995)
Posidonia sinuosa	12	Australia	Gordon et al. (1994)
Posidonia sinuosa	8-14	WA	Collier et al. (2007); Masini & Manning (1995)
Posidonia sinuosa	10-20	WA	Gordon et al. (1992)
Posidonia sinuosa	17	Australia	Gattuso et al. (2006)
Posidonia sinuosa	20	Australia	Gordon et al. (1994)
Posidonia sinuosa	24.7	SA	Duarte (1991); Dennison et al. (1993)

Posidonia coriacea

The minimum light requirements of *Posidonia coriacea* have been studied in South Australia (Spencer Gulf) and found to be in the order of 5-8% of Surface Irradiance (SI) (Duarte, 1991; Westphalen et al., 2004; Gattuso et al., 2006).

Posidonia angustifolia

The minimum light requirements of *Posidonia angustifolia* have been studied in a range of locations and environments in Western and South Australia. The values for the minimum light requirements of this species, as reported in literature, vary between 4 and 24.7% of Surface Irradiance (SI) (see Table 2 for overview).

Table 2. Minimum light requirements for *Posidonia angustifolia*, as reported in literature.

Seagrass species	%SI	Location	Reference
Posidonia angustifolia	4	SA	Collings et al. (2006)
Posidonia angustifolia	6.1	SA	Duarte (1991)
Posidonia angustifolia	6.2	SA	Gattuso et al. (2006)
Posidonia angustifolia	8.5	WA	Collier (2006) PhD thesis
Posidonia angustifolia	24.7	Waterloo Bay	Duarte (1991); Dennison et al. (1993)

Heterozostera tasmanica

The minimum light requirements of *Heterozostera tasmanica* have been exhaustively studied in a range of locations and environments in Victoria and South Australia. The values for the minimum light requirements of this species, as reported in literature, vary between 0.7 and 24.7% of Surface Irradiance (SI) (see Table 3 for overview).

Table 3. Minimum light requirements for *Heterozostera tasmanica*, as reported in literature.

Seagrass species	%SI	Location	Reference
Heterozostera tasmanica	0.7-8.2 (mean 2.9)		Gattuso et al. (2006)
Heterozostera tasmanica	2 - 7.2	SA	Duarte (1991)
Heterozostera tasmanica	2 - 9	VIC	Bulthuis (1983)
Heterozostera tasmanica	4.4	SA	Duarte (1991); Dennison et al. (1993)
Heterozostera tasmanica	5	VIC	Dennison et al. (1993)
Heterozostera tasmanica	5	VIC	Bulthuis (1983)
Heterozostera tasmanica	5	VIC	Warry & Hindrell (2009)
Heterozostera tasmanica	5-13	VIC	Kirkman et al. (2012); Bulthuis (1983)
Heterozostera tasmanica	9	VIC	Bulthuis & Woelkerling (1983)
Heterozostera tasmanica	10.4 (mean)		Lee et al. (2007)
Heterozostera tasmanica	17.4		Duarte (1991)
Heterozostera tasmanica	20.2	VIC	Dennison et al. (1993)
Heterozostera tasmanica	24.7	VIC	Duarte (1991)

Bulthuis and Woelkerling (1983) reported nearly 100%? survival of *Heterozostera tasmanica* for 10 months at 9% SI, reducing to 2-4 months survival at 2% SI. Kirkman et al. (2012) reported a 61% reduction in shoot density (due to mortality) after 3 months to <5% SI in a field shading experiment in western Port Phillip Bay (Victoria).

Zostera muellerii

The minimum light requirements of *Zostera muellerii* have been studied in several locations and environments in Queensland (esp. Moreton Bay) and New Zealand. The values for the minimum light requirements of this species, as reported in literature, vary between 16 and 36% of Surface Irradiance (SI) (see Table 4 for overview).

Table 4. Minimum light requirements for *Zostera muellerii*, as reported in literature.

Seagrass species	%SI	Location	Reference
Zostera muellerii	16-36	QLD	Longstaff (2003)
Zostera muellerii	30	QLD	Longstaff et al. (1999)
Zostera muellerii	30	QLD	Abal & Dennison (1996)

Kirkman (1978) documented survival of *Zostera muellerii* plants following three days of complete shading in tank experiments, but reported a complete loss of epiphytes. Schwarz et al. (2005) reported 40%SI as optimal conditions for the growth and survival of this species in New Zealand waters. Grice et al. (1996) reported only 1 month survival of this species at 5%SI, based on outdoor aquarium experiments in Moreton Bay.

Halophila australis

To our knowledge, no specific studies have been conducted on this particular species to investigate its minimum light requirements to date. However, there are taxonomic issues regarding this species, which is endemic to Australia, occurring along the southern coast from Perth to Victoria and in northern Tasmania. This temperate seagrass species is difficult to distinguish from the tropical species *Halophila ovalis* (which occurs in Western Australia, the Northern Territory and Queensland). Given the similar morphology and ecological niche of these species, it is assumed that *Halophila australis* has a similar tolerance for low light conditions as some of the other *Halophila* species. The minimum light requirements of several *Halophila* species have been studied in a range of locations around the world. The values for the minimum light requirements of *Halophila* species, as reported in literature, vary between 2.5 and 16 % of Surface Irradiance (SI) (see Table 5 for overview).

Table 5. Minimum light requirements for *Halophila* spp., as reported in literature.

Seagrass species	%SI	Location	Reference
Halophila decipiens	2,5	Hobe Sound, Florida, USA	Dennison (1987)
Halophila stlpulacea	3	Gulf of Eilat, Red Sea	Beer and Waisel (1982)
Halophila decipiens	4.4	St.Croix, Caribbean	Williams and Dennison (1990)
Halophila spp.	5	Sub tropical seas	Dennison et al. (1993)
Halophila decipiens	8.8	Northwest Cuba	Duarte (1991)
Halophila ovalis	16	Zanzibar, Tanzania	Schwarz et al. (2000)

3.1.2. Salinity

Tolerance to salinity is an essential requirement for seagrasses and they may encounter a wide range in the shallow coastal environments in which they occur (Walker and McComb, 1990). The optimum and range of salinities that can be tolerated varies among seagrass species (Lirman and Cropper, 2003). There are species which can tolerate a wide range of salinities, corresponding to their role of occupying shallow coastal areas subject to extreme salinity changes. Others tolerate just a narrow range. In general, experimentation shows that a wide range may be tolerated by several seagrass species for very short periods, but their long-term tolerances are narrower (Hillman et al., 1989). Low salinities have also been shown to have lethal effects on seagrasses. Many nearshore environments, where seagrasses occur, are subject to rapid changes in salinity from freshwater run-off. Some field studies on seagrasses suggest increased sensitivity to low salinities at high temperatures, but as yet no laboratory experiments on salinity/temperature interactions, or salinity interactions with most other environmental variables, have been carried out (Hillman et al., 1989).

Amphibolis antarctica

There are various references that refer to the salinity tolerance of *Amphibolis antarctica*. Walker (1985) reported healthy growth of this species in Shark Bay (WA) at salinities of 35-42 ppt, with optimum plant performance at 42 ppt and significant plant survival up to 57 ppt. Walker and McComb (1990) documented maximum seedling performance at 42.5 ppt, some seedling survival (but necrotic) at salinities of 50-57.5 ppt and mass mortality at 65 ppt within 5 days. Tyerman (1989) found this species growing in Shark Bay at salinities ranging from 37 to 64 ppt. Walker et al. (1988) reported optimum salinity for *Amphibolis antarctica* to be 35 ppt and higher, with 62.4 ppt as its upper limit. Edyvane (1999) reported healthy growth of this species at salinities >40 ppt in SA waters. Westphalen et al. (2005) observed that mature plants can tolerate prolonged exposure to 0 ppt (no effects after 72 h; initial effects after 2 weeks; full mortality after 6-7 weeks). Seedlings were affected by low salinity, showing significantly reduced photosynthesis if exposed for 72 h to <5 ppt, but no effects at 20 ppt and only minor effects at 10 ppt (Westphalen et al., 2005). Bryars and Collins (2005) observed significant mortality in mature plants if exposed to salinities <1 ppt for 7 weeks, while seedlings were clearly stressed or killed by salinities <10 ppt.

Amphibolis griffithii

No specific studies have been conducted on the tolerance of this species to salinity. In the absence of experimental data, we assume that the tolerance limits of *Amphibolis griffitthii* for salinity are similar to that of *Amphibolis antarctica*. Both species occur in roughly the same geographical areas of distribution.

Posidonia australis

Several studies have reported on the salinity tolerance of *Posidonia australis*. Tyerman et al. (1984) and Tyerman (1989) reported how the species was found growing in salinities ranging from 13 to 57 ppt, apparently unaffected at salinities as low as 13 ppt. Hillman et al. (1990) reported a normal seasonal salinity variation of 25-37 ppt in *Posidonia australis* meadows in WA, while Edyvane (1999) reported healthy growth at salinities over 42 ppt in SA waters. Walker et al. (1988) reported an optimum salinity for this species of 35 ppt and above, with an upper tolerance limit of ~55 ppt recorded in Shark Bay (WA). The species never occurs in persistently brackish conditions (Larkum, 1977).

Posidonia sinuosa

Two studies reported on tolerance limits of *Posidonia sinuosa* for salinity in SA waters. Westphalen et al. (2004, 2005) documented a considerable tolerance of this species to low salinity, surviving 72 hours at 0 ppt without effects, with initial effects only appearing after four weeks of continuous exposure to 0 ppt, and mortality setting in after 6 weeks. Bryars and Collins (2008) reported mortality of mature plants that were continuously exposed for 7 weeks to <1 ppt. Seedlings and seeds were clearly stressed or killed by <10ppt (Bryars and Collins, 2008).

Posidonia coriacea

Walker et al. (1988) reported optimum growth of *Posidonia coriacea* at salinities above 35 ppt, and a maximum upper tolerance limit of 50 ppt for this species in Shark Bay. No data are available on the tolerance of this species to low salinities. For the model, it is assumed to be similar to that of *Posidonia australis*.

Posidonia angustifolia

Two studies document the salinity tolerance of *Posidonia angustifolia* in SA waters. Bryars and Collins (2008) reported mortality of mature plants if exposed continuously for 7 weeks to <1 ppt. Westphalen et al. (2005) investigated the tolerance of the fruits of *Posidonia angustifolia* to salinity. Fruits were sensitive to low salinity treatments (72 h), with 100% mortality at 0 ppt, 75% mortality at 10 ppt, 40% mortality at 20 ppt and <20% mortality at 34 ppt. Seedlings / seeds of *Posidonia angustifolia* were stressed or killed when exposed to <10ppt (Bryars and Collins, 2008).

Heterozostera tasmanica

There is limited information available on the salinity tolerance of *Heterozostera tasmanica*. Westphalen et al. (2004) reported on the occurrence of *Heterozostera tasmanica* in SA estuaries (Westlakes), where it was found to tolerate prolonged exposure to ~15 ppt for 3 months. Edgar et al. (1994) observed a healthy *Heterozostera tasmanica* meadow growing at 33-38 ppt in Western Port, Victoria.

Zostera muellerii

Various studies have reported on the salinity tolerances of *Zostera muellerii*. Shepherd and Robertson (1989) found the species very tolerant to low salinity, even 0 ppt for several hours without effects. Brenchley and Probert (1998) reported lower seed germination at 22 ppt than at 32 ppt. Westphalen et al. (2004) noted that this species occurs in SA estuaries. Tyerman (1989) found the species growing in salinities of 3-37 ppt at Illawara Lake in NSW. The optimum salinity for *Zostera muellerii* is around 35 ppt, with a maximum salinity threshold ranging between 140 ppt (short-term) and 40 ppt (long-term), and a minimum salinity threshold varying between 0 ppt (short-term) to 10 ppt (long-term exposure) (Kerr and Strother, 1985; Touchette, 2007). Edgar et al. (1994) found a healthy *Zostera muellerii* meadow growing at 33-38 ppt in Western Port, Victoria. McKenzie (1994) reported a minimum salinity threshold of 9.5 ppt and a maximum of 33.5 ppt for *Zostera muellerii* in Queensland.

Halophila australis

There are no reports on the salinity tolerance of *Halophila australis*. In the absence of studies on *Halophila australis*, we have assumed that its salinity tolerance is similar to that of *Halophila ovalis*, with which it is often confused. Hillman and McComb (1988 a,b) found optimum salinities for *Halophila ovalis* in the Swan River estuary (WA) to range from 25-35 ppt, while surviving several months of exposure to reduced salinities of 15-20 ppt and tolerating increased salinities up to 42 ppt. Meadows experienced massive die-back when exposed to salinities <10 ppt for over 4 months due to heavy river discharge (Hillman and McComb, 1988 a,b). Benjamin et al. (1999) reported distinct differences in the salinity tolerance of marine and estuarine populations of *Halophila ovalis* (ecotypes). Marine *H. ovalis* plants appeared intolerant of prolonged exposure to low salinity (20%), showing 75% mortality within 3 weeks. Plants from estuarine populations of *H. ovalis* were healthy at 20 ppt and were growing well at 10 ppt, though they started to appear stressed after ~4 weeks (Benjamin et al., 1999).

3.1.3. Temperature

The temperature tolerance of seagrasses varies with geographical latitude. The range of thermal tolerance of tropical seagrass species is about half that of temperate seagrass species, whereas their upper tolerance limit is similar. Tropical and subtropical species do not tolerate cold temperatures and are only slightly more tolerant of extended periods of high temperatures than temperate species (Hillman et al., 1989). Intertidal seagrass populations, which are likely to be exposed to air at low tides, show greater tolerance of high temperatures than those which occur in deeper sites and remain submerged (McMillan, 1984). The growth of seagrasses in high (saturating) light environments increases with temperature, whereas growth of seagrasses in low light environments (near the light compensation point) decreases as temperature increases (Bulthuis, 1987). Temperatures above or below optimum limits might not necessarily destroy a meadow, but they might inhibit metabolism and thus decrease the plant’s productivity, although temperatures above their upper tolerance limits may cause substantial leaf mortality. At one occasion in Puerto Rico, *Thalassia testudinum* seagrasses lost their leaves at temperatures between 35-40°C, but their roots and rhizomes were unaffected, protected by the overlying sediments (Zieman, 1982). Sediments are poorer conductors of heat than seawater and they absorb heat more slowly. However, prolonged heating of the substrate may ultimately destroy the root and rhizome system as well (Zieman, 1982).

Amphibolis antarctica

There are various literature references that refer to the temperature tolerance of *Amphibolis antarctica*. Its optimum temperature has been variously reported as 23°C (Masini and Manning, 1997), 10-25°C (Walker and Cambridge, 1994) and 26°C (Walker and McComb, 1990). Walker and Cambridge (1994) reported seedling mortality at 30°C, but found full survival of seedlings at 10°C. In Shark Bay, Walker and McComb (1990) observed healthy growth at 18-26°C, while Masini and Manning (1997) quoted healthy meadow development in WA waters at 13-23°C. Reports by Griffin (2012) and Nayar et al. (2012) documented pristine meadows growing at 12-21.5°C in SA waters, while Seddon et al. (2000) reported on a large-scale die-back of *Amphibolis antarctica* in northern Spencer Gulf that was attributed to extreme conditions associated with a hot El Niño summer, with unusually low tide exposure (caused by dodge tides) coinciding with a period of prolonged high temperatures during January-February 1993 (max. air temperatures: 35–40°C; water temperature not quoted). Walker (1991) documented healthy meadows growing at 13-20°C in WA waters. Shepherd and Womersley (1981) reported this species as growing at 14-20°C in Waterloo Bay, SA.

Amphibolis griffithii

There are various literature references that refer to the temperature tolerance of *Amphibolis griffithii.* McMahon et al. (2008) found healthy growth of this species in WA waters at 18-23°C, but recorded a significant suppression of its photosynthetic rates at 13°C. Walker and Cambridge (1994) reported optimum temperatures for this species to be in the range of 15-20°C, with seedling mortality at 10°C, some seedling mortality at 25°C and full mortality of all seedlings at 30°C. Caruthers and Walker (1995) found *Amphibolis griffithii* growing at 15-22°C in Warnbro Sound (WA). Masini and Manning (1997) reported a similar optimum temperature range (13-23°C) for this species in WA waters. Ducker et al. (1977) and Short et al. (2010) noted a more limited temperature tolerance of this species if compared to *A. antarctica*.

Posidonia australis

A few studies have reported on the temperature tolerance of *Posidonia australis*. Walker and McComb (1988) found this species growing at 18-26°C (optimum 19°C) in Shark Bay, WA. Masini and Manning (1997) recorded a temperature range of 13-23°C (optimum 23°C) for this species in WA waters. Fong and Harwell (1994) reported a declining productivity of *Posidonia australis* at temperatures over 30°C. Shepherd and Womersley (1981) reported this species as growing at 14-20°C in Waterloo Bay, SA.

Posidonia sinuosa

Few studies have investigated the temperature tolerance of *Posidonia sinuosa*. Masini et al. (1995) and Masini and Manning (1997) documented healthy growth of this species in Princess Royal Harbour (WA) at 13-24°C (optimum: 18-23°C), but reported a 39% decline in photosynthetic rates when water temperature dropped to 13°C. Lee et al. (2007) reported 20.5°C as the optimum temperature for this species. Shepherd and Womersley (1981) reported this species as growing at 14-20°C in Waterloo Bay, SA.

Posidonia coriacea

No data are available on the tolerance of this species to temperature. It is assumed to be similar to that of *Posidonia australis* and *Posidonia sinuosa*. Shepherd and Womersley (1981) reported this species as growing at 14-20°C in Waterloo Bay, SA. Walker (1991) documented healthy meadows growing at 13-20°C in WA waters.

Posidonia angustifolia

Shepherd and Womersley (1981) reported this species as growing at 14-20°C in Waterloo Bay, SA. No other data are available on the tolerance of this species to temperature. It is assumed to be similar to that of *Posidonia australis* and *Posidonia sinuosa*.

Heterozostera tasmanica

There is limited information available on the temperature tolerance of *Heterozostera tasmanica*. Bulthuis (1987) noted a particularly wide tolerance of this species for temperature in Victorian waters, ranging from 5-40°C. The optimum temperature for this species has been reported as 30°C (Bulthuis, 1983; Builthuis, 1987; Lee et al., 2007). Edgar et al. (1994) found a healthy meadow of *Heterozostera tasmanica* growing at 10-22°C in Western Port (Victoria). Shepherd and Womersley (1981) reported this species as growing at 14-20°C in Waterloo Bay, SA.

Zostera muellerii

Various studies have reported on the temperature tolerances of *Zostera muellerii*. Edgar et al. reported healthy meadows of *Zostera muellerii* growing at 10-22°C in Western Port, Victoria. Collier et al. (2011) noted 19-30°C as the temperature range for sustained health of this species in Queensland, observing signs of severe stress at 33°C. McKenzie (1994) reported healthy growth of this species at water temperatures ranging from 20-33°C near Cairns Harbour, northern Queensland. Campbell et al. (2006) documented a drastic decline in meadows of this species at temperatures of 35°C and above. Fong and Harwell (1994) observed declining productivity in *Zostera muellerii* plants at temperatures above 30°C.

Halophila australis

Few data are available on the tolerance of this species to temperature. Fong and Harwell (1994), who noted declining productivity of this species at temperatures over 30°C. Shepherd and Womersley (1981) reported this species as growing at 14-20°C in Waterloo Bay, SA. In the absence of more specific studies on *Halophila australis*, we have assumed that its temperature tolerance is similar to that of *Halophila ovalis*, with which it is often confused. Den Hartog (1970) recorded a lower temperature limit for *Halophila ovalis* of 10°C. *Halophila ovalis* growth is reduced at temperatures above 37°C and conditions above 40°C for an extended time are considered lethal (Lee et al., 2007).

3.1.4. Flow velocity

Forces generated by water motion originating from tides and wind can have a measurable effect on growth and distribution of seagrasses. For example, high wave energy may prevent seagrasses from becoming established (due to the drag exerted on the plants and/or the constant shifting of sediment particles) even when the light requirements for seagrass growth are met (Koch, 2001). Increasing flow can enhance the nutrient uptake in seagrasses by reducing the boudary layer around the leaves. Studies on eelgrass (Fonseca and Kenworthy, 1987; Koch, 2001) suggest that there may be an optimum current speed below which metabolism is limited by diffusion and above which growth may decline as a result of physical disruption of the plants. Seagrass beds themselves reduce current velocity by extracting momentum from the moving water. The magnitude of this process depends on the density of the seagrass bed (Koch, 2001). Some seagrass species manage to exist in areas characterised by high currents, but then their ability to reduce the turbulence is virtually eliminated and they most likely to depend more on their root system for nutrient uptake (Scoffin, 1970; Fonseca and Kenworthy, 1987). A reduction in current flow or wave energy may cause a higher degree of sedimentation and reduced nutrient availability, and thus adversely affect seagrass growth. If increased current current flow results in erosion of sediments, this may trigger the self-perpetuating destruction of the meadow. Current flow is also important in pollination of seagrasses and in the dispersal of seagrass seeds and propagules. Although often overlooked, hydrodynamic parameters are crucial in determining the habitat suitability of an area for seagrasses (Koch, 2001).

There is very limited information available on the species-specific tolerance limits to flow velocity for the species occurring in Adelaide’s coastal waters. Instead, we have therefore adopted a more general set of flow velocity tolerance thresholds (same for all species) that is based on available information on any seagrass species in the literature:

***Zostera* spp.**

Koch (2001) concluded in her study on the subject that intermediate current velocities between 5 and 100 cm s^{-1} are needed to support healthy *Zostera marina* growth in Chesapeake Bay (USA). Fonseca and Kenworthy (1987) mention 16 cm s^{-1} as the lowest threshold, 20-40 cm s^{-1} as optimum and 50 cm s^{-1} as the upper threshold velocity to sustain healthy *Zostera marina* beds in the USA. Conover (1964) reported an upper threshold of 50 cm s^{-1} for this species. Others have reported much higher upper threshold values of 120 m s^{-1} (Scoffin, 1970) and 150 cm s^{-1} (Fonseca et al., 1982). Fonseca et al. (1983) distinguished low (<50 cm s^{-1}), medium (50-90 cm s^{-1}) and high (>90 cm s^{-1}) current regimes in their study on flow dynamics along transects through *Zostera marina* meadows in the USA, and concluded that *Z. marina* can tolerate current velocity up to a maximum of approximately 120-150 cm s^{-1} in the areas studied. Based on a series of extensive experimental field studies on the impact of hydrodynamics (in particular tidal currents) on the development and morphology of intertidal *Zostera noltii* beds in the German Wadden Sea, using an in situ ‘three current flume’ that could experimentally modify current flows over seagrass at a site, Schanz and Asmus (2003) demonstrated that the optimum current velocities for *Zostera noltii* were between 4 and 8 cm s^{-1}, with reduced growth at current velocities greater than 8 cm s^{-1}.The maximum current speeds which *Zostera noltii* plants were able to tolerate was ~33 cm s^{-1} (Schanz and Asmus, 2003). Schwarz et al. (2005) noted that flow velocities suitable for *Zostera muellerii* growth generally are below 50 cm s^{-1}, based on studies in New Zealand waters.

***Posidonia* and *Amphibolis* spp.**

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Van Keulen and Borowitzka (2002) noted that *Posidonia australis* and *Amphibolis griffitthii* could withstand flows of at least 25 cm s^{-1}. Warry and Hindrell (2009) noted that in Victorian waters, *Amphibolis antarctica* occupies areas of higher flow.

Summary

From the positive and negative effects of reduced current velocities found in seagrass meadows in general, it can be concluded that seagrass plants will benefit from intermediate currents. Recent literature reviews (Koch, 2001; Koch et al., 2006a) of available quantitative information on this topic suggests that most seagrasses tolerate current velocities between 5 and 100 cm s^{-1}. Currents below 5 cm s^{-1} have been suggested as limiting to seagrasses due to a reduction in the flux of carbon and nutrients to the leaf surface, while at flow velocities below 3 cm s^{-1} no seagrass growth seems possible (Koch, 2001). Flow velocities above 100 cm s^{-1} can hamper successful seedling establishment and few (if any) seagrasses can tolerate flow velocities as high as 150 cm s^{-1}, above which the plants are easily uprooted by the flow.

3.1.5. Low tide exposure

The degree to which seagrasses can withstand low tide exposure differs between species. In the intertidal, seagrasses and seaweeds are periodically exposed to air where they experience a variety of potentially stressful environmental conditions, including desiccation, high light, nutrient limitation, high and low temperature, and osmotic stress (Davison and Pearson, 1996). In turbid waters, the optimum position of seagrasses in the intertidal zone is considered to be a compromise between desiccation and light conditions. The period during which a seagrass plant is exposed during low tide is essentially a function of the tidal amplitude and the depth at which the seagrass plant occurs, although wind stress may occasionally propel nearshore water levels up to higher levels than would be expected. Besides, intertidal seagrass plants are not always entirely exposed as a thin lens of water is often retained due to micro-variations in bottom-topography. The duration of the exposure period fluctuates over the tidal (spring-neap) cycle. Low tide exposure in this study is defined and expressed as the average percentage of the time that the plants are exposed.

Amphibolis antarctica

Amphibolis antarctica only occurs in subtidal areas and will suffer mortality due to desiccation if exposed at low tide (Seddon et al., 2000; Warry and Hindrell, 2009).

Amphibolis griffithii

Amphibolis griffitthii only occurs in subtidal areas and will suffer mortality due to desiccation if exposed at low tide.

Posidonia australis

Although *Posidonia australis* tends to occur in shallower areas than the other *Posidonia* spp., it only occurs in subtidal areas (data from Victoria and South Australia) and will suffer mortality due to desiccation if exposed at low tide (Shepherd and Robertson, 1989; Seddon et al., 2000; Warry ~~and~~ Hindrell, 2009).

Posidonia sinuosa

Posidonia sinuosa only occurs in subtidal areas and will suffer mortality due to desiccation if exposed at low tide.

Posidonia coriacea

Posidonia coriacea only occurs in subtidal areas and will suffer mortality due to desiccation if exposed at low tide.

Posidonia angustifolia

Posidonia angustifolia only occurs in subtidal areas and will suffer mortality due to desiccation if exposed at low tide.

Heterozostera tasmanica

Heterozostera tasmanica can tolerate some limited exposure at low tide and as such is sometimes found in intertidal areas (Robertson, 1984), but it more typically occurs subtidally to 3-4 m deep, depending on the turbidity of the water (Warry and Hindrell, 2009). Clarke and Kirkman (1989) found that experimental transplants of *Heterozostera tasmanica* were unable to survive significant desiccation in intertidal areas in Western Port (Victoria) where *Zostera muellerii* thrived.

Zostera muellerii

Zostera species appear more tolerant of aerial exposure and the resulting desiccation stress than most other seagrasses and have the ability to fix atmospheric carbon during short exposures (Leuschner and Rees, 1993; Leuschner et al., 1998). In South Australian waters, *Zostera muellerii* occurs in intertidal areas, where it is able to tolerate exposure at low tide (Robertson, 1984). Studies by Schwarz et al. (2005) in New Zealand indicate that the optimal duration of low tide exposure for *Zostera muellerii* is between 2 and 5 hours. Plants were unable to tolerate more than 6 hours of low tide exposure and were stressed in these turbid waters when exposed less than one hour due to insufficient light (Schwarz et al., 2005). McKenzie (1994) reported this species as being tolerant of low tide exposure for up to 6895 minutes (115 hours) per month in Queensland waters, although plants also grew subtidally. *Zostera muellerii* appears to be predominantly intertidal in Victoria and South Australian waters (Warry and Hindrell, 2009; Bryars and Rowling, 2009). Clarke and Kirkman (1989) describe the species as being very tolerant of intertidal exposure, thriving on intertidal mudbanks in Western Port (Victoria), able to tolerate long periods of low tide exposure.

Halophila australis

No data are available on the tolerance to low tide exposure of *Halophila australis*, a species that occurs from 0 to 23 m depth in Adelaide coastal waters, often as an understorey component to other larger species (Westphalen et al., 2005). In the absence of specific studies on *Halophila australis*, we have assumed that its tolerance to low tide exposure is similar to that of *Halophila ovalis*, with which it is often confused. *Halophila ovalis* is tolerant to several hours of air exposure at low tide (Björk et al. 1999), as a result of which it can occupy significant areas in the upper intertidal. Its leaf stems are fine and unable to support the leaves when the tide recedes, resulting in the leaves lying flat against the substrate and often submerged in small pools of water or thin films of remaining water, potentially providing protection against air exposure (Björk et al. 1999). Consequently, the main sensitivity of *Halophila ovalis* at low tide is to high light intensities (resulting in photosynthetic stress), rather than desiccation due to exposure to air (Petrou et al., 2013). Durations of air exposure tolerated by *Halophila ovalis* were in the order of up to ~4 hours in Zanzibar and Queensland (Björk et al., 1999; Petrou et al., 2013). In upper intertidal areas in Queensland, *Halophila ovalis* grows together with *Zostera muellerii*, a species known to tolerate up to 6 hours of exposure (see above).

3.1.6. Sediment composition

Where space is available, seagrass populations can only develop if the substrate is suitable. Most seagrass species are confined to sandy to muddy sediments, which are easily penetrated by seagrass roots, although some species can grow on rubble and over rock (Hemminga and Duarte, 2000). High mobility of fine sediments, in which currents and wave-induced bedload transport generate large sand ripples and sand waves, renders them unsuitable to support plant growth. These processes cause successive burial and erosion, which may cause seagrass mortality, depending on the size and frequency of these events relative to the life history and growth capacity of the species. Hence, highly mobile, but otherwise suitable, sandy sediments may be bare of seagrass cover (Hemminga and Duarte, 2000). Marine sediments can be hostile habitats for plant life, particularly where inputs of organic matter are excessive. High inputs of organic matter stimulate bacterial activity, raising the anoxic layer closer to the sediment surface and leading to the development of bacterial communities with metabolic pathways that result in the accumulation of phytotoxic compounds, such as sulphide (Hemminga, 1998). Seagrasses may counterbalance these stresses by pumping oxygen through their roots into the sediments, thereby maintaining a relatively oxidized rhizosphere. Sediments with higher organic matter concentrations are likely to support high bacterial activity, driving the sediment to a reduced status, reflected in highly negative redox potential (Hemminga and Duarte, 2000). Sediment pore-water redox was also found to be an important determinant for seagrass suitability in West European coastal waters (Van der Heide et al., 2009). In some of the literature on habitat preferences of seagrasses, substratum type and water motion are considered together because of the close linkage between sediment grain-size composition and the degree of exposure to tides and currents (Davison and Hughes, 1998).

Sediments within seagrass beds are usually finer than those in adjacent unvegetated areas due to trapping of fine sediments by the seagrass canopy, which can slow down currents and attenuate wave energy (depending on the density of the vegetation). Siltation-derived changes in sediment conditions in a Philippine seagrass meadow, tested in outdoor tank experiments, did not negatively affect plant growth and survival (Halun et al., 2002).

Amphibolis antarctica

Warry and Hindrell (2009) reported the dominant substrate type for *Amphibolis antarctica* in Victorian waters as coarse sandy sediments.

Amphibolis griffithii

Substrate types occupied by *Amphibolis griffitthii* in the sublittoral zone vary from sandy floors, sand-covered rocks and gravel bottoms to banks of firm, compact clay in places where the water is kept continually in motion by currents or wave action (Short et al., 2010).

Posidonia australis

In South Australian waters, *Posidonia australis* prefers shallow, sheltered environments (Bryars and Rowling, 2009). Similarly, in New South Wales it is found on soft sedimentary environments at protected/sheltered sites.

Posidonia sinuosa

In Western Australia, *Posidonia sinuosa* is found on a range of substrate types, ranging from fine to coarse sediments with variability between sites and seasons (Van Keulen and Borowitzka, 2003).

Posidonia coriacea

Posidonia coriacea is part of the *Posidonia ostenfeldii* complex. The *P. ostenfeldii* group of species is typically found in open ocean or rough water sublittoral habitats, and some aspects of their morphology and anatomy appear to be associated with the features of such habitats, particularly the strong wave movement and mobile sand substrate (Cambridge and Kuo, 1984).

Posidonia angustifolia

Posidonia angustifolia has rather thin, flexible leaves and usually inhabit sheltered waters (Cambridge and Kuo, 1979).

Heterozostera tasmanica

In South Australia, *Heterozostera tasmanica* was found to form healthy meadows on sandy substrates with 2.8 to 30.9% fines (Edgar and Shaw, 1995).

Zostera muellerii

In Queensland, *Zostera muellerii* inhabits muddy estuarine areas (Collier et al., 2011). In South Australia, *Zostera muellerii* was found to form healthy meadows on soft substrates with 0.5 to 72% fines (Edgar and Shaw, 1995). The species tends to dominate in areas with higher %fines (McKenzie, 2007).

Halophila australis

In Victoria, *Halophila australis* occurs on finer silts and muds (Roob et al., 1998; Warry and Hindrell, 2009). Bryars and Rowling (2009) described this species as a colonizer of bare sand disturbed by dredging in South Australian waters.

3.1.7. Exposure to wave action

In their natural environment, seagrasses are exposed to wind-driven currents, tides, waves and wave-driven currents. While these hydrodynamic processes affect seagrasses, seagrasses also affect these hydrodynamic processes through the attenuation of currents and waves (Koch et al., 2006a). Excessively weak currents and waves may lead to detrimentally high sediment organic contents or lead to limiting leaf diffusive boundary layer conditions. In contrast, in areas with high wave exposure and strong currents, seagrass may be damaged due to excessive sediment transport, which does not allow seeds to become established, or eroding/burying existing seagrass beds. As a result, wave- or current-exposed areas tend to have patchy seagrasses or are unvegetated (Koch et al. 2006b). The temporal statistics of waves relevant to seagrass loss are described by maxima during events with a relevant return period. How long this relevant return period is, depends on how long it takes the seagrass to grow back in areas where it was affected by waves, under otherwise suitable conditions. Literature data on exposure to wave action have been expressed in various ways, including significant wave height, (swell) wave period and wave energy (J m^{-2}). Another, potentially more useful measure to express and predict seagrass tolerance ot wave energy is the near-bottom orbital velocity (H_s). Infantes et al. (2009) observed that a near-bed orbital velocity of 0.38-0.42 m s^{-1} defined the upper depth limit for *Posidonia oceanica.* De Jong et al. (2005) reported a bed orbital velocity of 0.4 m s^{-1} as the limit for *Zostera marina*.

Amphibolis antarctica

Amphibolis antarctica is adapted to hydrodynamically active environments, although particularly high hydrodynamic energy in areas off the Adelaide coast were found to prevent seedling establishment (Wear et al., 2010). Clarke and Kirkman (1989) state that '*Amphibolis antarctica* is the only species in WA capable of colonizing high intensity disturbance sites (ocean swell)'. In a field study in Western Australia, Verduin and Backhaus (2000) found this species able to withstand wave periods of up to 15 seconds, attenuating wave energy with as much as 6.25 J m^{-2}.

Amphibolis griffithii

Similar to *A. antarctica, Amphibolis griffithii* is able to tolerate substantial wave energy and swell. In WA waters, Van Keulen and Borowitzka (2002) found this species able to withstand 1-1.5 m swell. In their excellent review report on waves in seagrass systems, Koch et al. (2006b) describe this species as a robust 'wave-tolerant' seagrass species.

Posidonia australis

Posidonia australis is able to withstand significant hydrodynamic energy from wave action and swell. In WA waters, Van Keulen and Borowitzka (2002) found this species able to withstand 1-1.5 m swell. However, Bryars and Rowling (2009) describe this species as preferring shallow sheltered environments in South Australian waters. Ruiz-Montoya et al. (2012) reported how stormy weather with a significant wave height of 2-3 m dislodged seedlings of this species.

Posidonia sinuosa

In South Australia, *Posidonia sinuosa* is described as a species that prefers growing at moderate wave exposure with a mean annual wave height of approx. 1 m (Irving et al., 2010). Cambridge and Kuo (1979) describe this as a species with thin, flexible leaves and thus usually inhabiting relatively sheltered waters.

Posidonia coriacea

Posidonia coriacea is described as a species adapted to much higher wave energy environments that *Posidonia angustifolia* and *P. sinuosa*. In their excellent review report on waves in seagrass systems, Koch et al. (2006b) describe this species as a robust 'wave-tolerant' and 'swell-tolerant' seagrass species.

Posidonia angustifolia

This species seems to favour deeper waters (2-35 m) (Westphalen et al., 2005). Cambridge and Kuo (1979) describe this as a species with thin, flexible leaves and thus usually inhabiting relatively sheltered waters.

Heterozostera tasmanica

A study in Holdfast Bay (SA) documented how *Heterozostera tasmanica* only forms meadows of significant extent in shallow areas with low wave action (often found in blow-outs) (Clarke and Kirkman, 1989).

Zostera muellerii

There is no specific information on the tolerance of *Zostera muellerii* to wave exposure. However, judging from its typical distribution in the intertidal, usually on areas of fine muddy sediment (see sections above), it seems plausible to assume that the species is probably quite sensitive to significant wave action and prefers shallow sheltered environments.

Halophila australis

In Victoria, *Halophila australis* occurs in deeper waters (>2-3 m) (Roob et al., 1998), often growing in association with *Heterozostera tasmanica* at the deeper margins of *Heterozostera* distribution (Warry and Hindrell, 2009). The species is often found in blow-out areas (along with *Heterozostera tasmanica*) (Ruiz-Montoya et al., 2012). Ruiz-Montoya et al. (2012) reported how stormy weather with a significant wave height of 2-3 m dislodged seedlings of this species.

3.1.8. Sedimentation and erosion

Several studies have documented deterioration of seagrass meadows by smothering due to excessive sedimentation. Seagrass species that develop vertical shoots (e.g. *Cymodocea, Thalassia, Thalassodendron* and *Amphibolis*) may respond to fluctuations in sediment depth by modifying their vertical (i.e. plagiotropic) growth to relocate their leaf-producing meristems closer to the new sediment level, but there are limits to the level of sedimentation seagrasses can tolerate (Marba and Duarte, 1994). Vermaat et al. (1997) reported sedimentation rates of 10-13 cm yr^{-1} as the maximum threshold value of what seagrasses in the Philippines and Spain can survive. Manzanera et al. (1995) reported significant mortality of shoots of the seagrass *Posidonia oceanica* in response to experimental over-sedimentation, even at moderate burial levels (ca. 5 cm). Settlement of suspended material on leaf blades of seagrasses may interfere significantly with photosynthesis, and appears especially significant in low wave energy environments where fine sediments are present and can settle out (Shepherd et al., 1989). The impact of sedimentation is often increased where epiphytes are abundant on seagrass leaves (for instance under nutrient enriched conditions) because epiphitized leaf blades collect a greater amount of sediment. In the case of eelgrass (*Zostera marina*) the blades and epiphytes then appear dull brown coated with a fine layer of sediment, and they often sink to the bottom (Short et al., 1995).

An indication of the duration that seagrasses can tolerate high rates of sedimentation was revealed by field experiments in Spain. Artificial burial of the seagrass *Posidonia oceanica* with as much as 15 cm of sediment caused 100% mortality after 200 – 300 days (Manzanera et al., 1995). Sudden burial of *Cymodocea nodosa* with 5 cm of sediment resulted in 90% mortality after 35 days, but those surviving responded with a considerable shoot elongation (Marba and Duarte, 1994). Some individual shoots of this species were able to survive burial as great as 7 cm (Marba and Duarte, 1994).

Amphibolis antarctica

Clarke (1987) reported that *Amphibolis antarctica* in SA waters can tolerate sediment deposition up to 10 cm with no adverse effects on its growth. Clarke and Kirkman (1989) carried out manipulative experiments in Holdfast Bay (SA) and found that under anoxic conditions (using fine sediments, rich in organic matter), *Amphibolis antarctica* plants survived less than 1 week under full burial. *Amphibolis antarctica* was found to be very tolerant to erosion, surviving removal of the entire sediment top layer up to the depth of the rhizomes for as long as 6 months (Clarke and Kirkman, 1989).

Amphibolis griffithii

In SA waters, *Amphibolis griffithii* is able to tolerate sediment deposition up to 10 cm with no adverse effects on its growth (Clarke, 1987). Studies in West Australian waters, however, showed significant losses of transplanted shoots of this species in areas of erosion of -4.5 to -8.5 cm (Paling et al., 2003). Van Keulen and Borowitzka (2002) documented how storm events in WA led up to -35 cm of erosion at sites dominated by *Amphibolis griffithii*, concluding that this species was less capable of stabilising the sediment than *Posidonia australis*.

Posidonia australis

There is a range of studies that document the tolerance of *Posidonia australis* to sedimentation and erosion. Based on burial experimental, Cabaco et al. (2008) reported that *Posidonia australis* can tolerate burial with up to 15 cm with less than 10% mortality of its shoots. Burial with 19.5 cm caused 50% shoot mortality, while burial with 30 cm resulted in 90% mortality (Cabaco et al., 2008). In a study in WA, Nelson and Paling (in prep.) found that burial with 30 cm resulted in significant adverse effects on rhizome growth in this species. Chisholm (2009) reported no impacts at erosion of -2 cm, no impacts of burial up to 8 cm, 10% mortality at 15 cm burial and total mortality at 16 cm, suggesting the critical threshold for burial between 8 and 16 cm for this species. In a study at Holdfast Bay (SA), burial with 10 cm caused reduced growth in *Posidonia australis* but plants survived complete burial for up to 4 months if the sediment remained aerobic (Clarke, 1987; Clarke and Kirkman, 1989). Erosion of -20 to -25 cm led to a slow demise of the plants (Clarke and Kirkman, 1989). Based on experiments carried out in WA, Nelson (1992) and Nelson and Paling (in prep.) documented survival of *Posidonia australis* for 3-4 months when buried with >30 cm of sediment.

Posidonia sinuosa

Cabaco et al. (2008) reported <30% mortality of *Posidonia sinuosa* when buried with <10 cm of sediment, 50% mortality at 15.4 cm burial and 95% mortality at 30 cm burial. Nelson (1992) found plants of this species surviving complete burial for at least 3-4 months in WA.

Posidonia coriacea

Paling et al. (2003) found that erosion with -4.5 to -8.5 cm led to high losses of transplanted shoots of *Posidonia coriacea* in WA. Van Keulen and Borowitzka (2002) documented how storm events led up to -35 cm of erosion at sites that had substantial stands of this species, concluding that this species was less capable of stabilising the sediment.

Posidonia angustifolia

Complete burial of *Posidonia angustifolia* with 60 cm of sediment reduced growth but did not result in mortality of this species after 4 months, as long as the sediment was still aerobic. Anoxic conditions resulted in mortality within 2 weeks (Clarke, 1987).

Heterozostera tasmanica

Clarke and Kirkman (1989) describe *Heterozostera tasmanica* as vulnerable to sediment deposition, causing 'coating' of its leaves (especially in the intertidal).

Zostera muellerii

Seddon (2000) describes *Zostera muellerii* in SA waters as sensitive to burial and sedimentation. Waycott et al. (2007) reported how sedimentation with 10 cm caused a total loss of this species at a site in Queensland.

Halophila australis

Based on an experimental study in WA, Ooi et al. (2011) reported how *Halophila australis* is able to tolerate sediment deposition up to 4 cm with no adverse effects on its growth. Burial with 8 cm resulted in nearly full mortality (Ooi et al., 2011). In an experiment in Holdfast Bay (SA), Clarke and Kirkman (1989) observed how this species did not survive full burial for more than 1 week. The species was, however, described as a rapid colonizer (between perturbations) in areas with high siltation (Clarke and Kirkman, 1989).

3.2. Summary of critical thresholds for Adelaide's seagrass species

The following tables summarize the values reported in the literature for the minimum, optimum and maximum values of various environmental parameters tolerated by the different seagrass species in Adelaide waters, as described in detail in the preceding sections of this chapter.

Table 3.1 Literature data on critical thresholds for *Amphibolis antarctica*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS

Thresholds (literature values) to determine habitat suitability (HSI)

Species: ***Amphibolis antarctica***

parameter	minimum tolerated	optimum range	maximum tolerated	literature reference	geographic area
sediment composition		occupies coarse sandy sediments		Warry & Hindrell (2009)	VIC
(%fines)					
current velocity		occupying areas of higher flow		Warry & Hindrell (2009)	VIC
(cm/sec)				Fonseca et al. (2002); Kendrick et al. (2008)	
light regime	24.7 %SI (MLR)			Duarte (1991); Dennison et al. (1993)	VIC
(%SI)	<5% SI at maximum depth limit (18 m)			Bryars & Collins (2008)	SA
	max. depth limit for most Amphibolis in Adelaide Coastal Waters is ~12 m			Bryars and Rowling (2009)	SA
	no mortality if shaded to 0%SI for 6 weeks, but loss of nearly all epiphytes			Bryars & Collins (2008)	SA
salinity		35 - 42 ppt (optimum = 42 ppt)	survival at 57 ppt	Walker (1985)	WA
(ppt)		max leaf prod at 42.5 ppt (seedlings)	seedling mortality at 65 ppt within 5 d	Walker & McComb (1990)	WA
			(some survival at 50-57.5 ppt but necrotic)		
		found growing in salinities of 37-64 ppt		Tyerman (1989)	Shark Bay (WA)
		35-42.5 ppt	57.5 ppt upper survival limit	Koch et al. (2007)	WA
		35 and higher	62.4 ppt upper limit	Walker et al. (1988)	WA, Shark Bay
		healthy growth at >40 ppt		Edyvane (1999)	SA
	plants tolerate prolonged exposure to 0 ppt	seedlings affected by low salinity		Westphalen et al. (2005)	SA
	(no effects if 72 hrs); initial effects after 2 wks;	(i.e. reduced photosynthesis if			
	full mortality after 6-7 weeks)	exposed for 72 h to <5 ppt); but no effects at 20 ppt, minor effect at 10 ppt			
	mortality if exposed 7 weeks to <1 ppt			Bryars & Collins (2008)	SA
	Seedlings / seeds clearly stressed or killed by <10ppt			Bryars & Collins (2008)	SA
temperature		23 °C (optimum)		Masini & Manning (1997)	WA
(°C)		26 °C (optimum)		Walker & McComb (1990)	WA
		10-25°C	(seedling)mortality at 30°C	Walker & Cambridge (1995)	WA
		full survival of seedlings at 10°C			
		18-26°C (optimum 26°C)		Walker & McComb (1988)	Shark Bay, WA
		13-23°C (optimum 23°C)		Masini and Manning (1997)	WA
		14-20°C		Shepherd and Womersley (1981)	Waterloo Bay, SA
		13-20°C (winter min. - summer max.)		Walker 1991	WA
		growing at 12-21.5°C (pristine meadows in SA)		Griffin (2012); Nayar et al. (2012)	SA
			die-back caused by high temperature?	Seddon et al. (2000)	Spencer Gulf, SA
low tide exposure	0 (will die if exposed at low tide)	occurs in subtidal areas		Warry & Hindrell (2009)	VIC
(h/day)	exposure at low tide will cause mortality			Seddon et al. (2000)	SA
sedimentation		up to 10 cm (no effects on growth)		Clarke (1987)	SA
(mm)			less than 1 wk survival of full burial (anoxic)	Clarke & Kirkman (1989)	Holdfast Bay, SA
	more tolerant to erosion (to depth of rhizome - survived for 6 months) than Posidonia			Clarke & Kirkman (1989)	Holdfast Bay, SA
	erosion (removal of 20-25 cm) led to slow demise			Clarke & Kirkman (1989)	Holdfast Bay, SA
wave attenuation	6.25 J m-2 (attenuation)			Verduin and Backhaus (2000)	WA
	wave period: 15 sec				
Wave exposure index		hydrodynamically active environment (high energy)		Wear et al. (2010)	SA
		(off Adelaide) prevents seedling establishment			
		A. antarctica is the only species capable		Clarke & Kirkman (1989)	WA
		of colonising high intensity disturbance sites (ocean swell)			

Table 3.2 Literature data on critical thresholds for *Amphibolis griffithii*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS
Thresholds (literature values) to determine habitat suitability (HSI)

Species: ***Amphibolis griffithii***

parameter	minimum tolerated	optimum range	maximum tolerated	literature reference	geographic area
sediment composition		on sandy floors, sand covered rocks,		Short et al. (2010)	
(%fines)		gravel bottoms and banks of compact clay			
current velocity		withstanding flows of at least 25 cm/s		Van Keulen & Borowitzka (2002)	WA
(cm/sec)					
light regime	>>20% SI (=Minimum Light Requirement)			McMahon & Lavery (2008)	WA
(%SI)	severe stress if sustained shading to 19 %SI				
	loss of 72% leaf biomass if shaded to 5-18% SI			McMahon et al. (2011)	WA
	for 3 months but fast recovery				
	89-100% leaf loss and no recovery if			McMahon et al. (2011)	WA
	shaded to 6-9 %SI for 6-9 months				
	significant decline in growth and biomass when shaded to 88% of			Mackey et al. (2007)	WA
	ambient light levels for 3 months, but swift recovery after removal of shades				
	sugar compounds stored in rhizomes of Amp. Griff. Can only support less than 1 day's total respiration			Carruthers & Walker (1997)	WA
	unlike Posidonia spp. (with a much greater proportion of below-ground biomass and therefore storage potential				
salinity					
(ppt)					
temperature	photosynth. rate suppressed at 13 °C	18-23 °C (healthy growth)		McMahon & Lavery (2008)	WA
(°C)	(seedling) mortality at 10°C	15-20°C	some seedling mortality at 25°C	Walker & Cambridge (1995)	WA
			full mortality at 30°C (seedlings)		
		13-23°C (optimum 23°C)		Masini and Manning (1997)	WA
		limited temperature tolerance (less than A. antacrtica)		Short et al. (2010); Ducker et al. (1977)	
		found growing at 15-22°C		Caruthers and Walker (1995)	Warnbro Sound, WA
low tide exposure	0 (will die if exposed at low tide)				
(h/day)					
sedimentation		up to 10 cm (no effects on growth)		Clarke (1987)	SA
(mm)	-4.5 to -8.5 cm erosion led to high losses of transplanted shoots			Paling et al. (2003)	WA
	(storm events led up to -35 cm erosion events at some sites)		less able to stabilise sediment	Van Keulen and Borowitzka (2002)	WA
			than Posidonia australis		
Wave exposure index		able to withstand 1-1.5 m swell		Van Keulen and Borowitzka (2002)	WA
		a more robust 'wave-tolerant' species		Koch (ERDC report on waves)	

Table 3.3 Literature data on critical thresholds for *Posidonia australis*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS

Thresholds (literature values) to determine habitat suitability (HSI)

Species: ***Posidonia australis***

parameter	minimum tolerated	optimum range	maximum tolerated	literature reference	geographic area
sediment composition		prefers shallow sheltered environments		Bryars and Rowling (2009)	SA
(%fines)		In NWS, found on soft sedimentary		West et al. (1989)	NSW
		environments at protected/sheltered sites			
current velocity		withstanding flows of at least 25 cm/s		Van Keulen & Borowitzka (2002)	WA
(cm/sec)					
light regime		requires >> more light than P. sinuosa		Masini et al. (1995)	WA
(%SI)	10%SI (MLR)	mortality if <10% for >3 months		Fitzpatrick & Kirkman (1995)	NSW
	5%SI: caused rhizome necrosis after 132 days			Nelson & Paling (in prep.)	WA
salinity	unaffected at 13 ppt or more	found growing in salinities of 13-57 ppt		Tyerman et al. (1984); Tyerman (1989)	Australia
(ppt)		25-37 ppt (normal seasonal variation)		Hilman et al. (1990)	WA
		healthy growth at >40 ppt		Edyvane (1999)	SA
		35 ppt and above	55 ppt upper limit	Walker et al. (1988)	WA, Shark Bay
		never occurs in persistently brackish conditions		Larkum (1977)	Australia
temperature		18-26°C (optimum 19°C)		Walker & McComb (1988)	Shark Bay, WA
(°C)		13-23°C (optimum 23°C)		Masini and Manning (1997)	WA
			>30 °C (declining productivity)	Fong & Harwell (1994)	Australia
		14-20°C		Shepherd and Womersley (1981)	Waterloo Bay, SA
low tide exposure	0 (will die if exposed at low tide)	inhabits shallow subtidal areas		Warry & Hindrell (2009)	VIC
(h/day)		occurs in shallower areas than other Posidonia spp.		Shepherd and Robertson (1989)	
	mortality if exposed at low tide			Seddon et al. (2000)	SA
sedimentation		less than 15 cm burial (<10% mortality)	50% shoot loss at 19.5 cm burial	Cabaco et al. (2008)	
(mm)			still 10% survival at 30 cm burial		
			>30 cm burial affected rhizome growth	Nelson & Paling (in prep.)	WA
	no impacts at erosion of -2 cm	no impacts of burial up to 8 cm	critical threshold between 8 & 16 cm	Chisholm (2009)	WA
		10% mortality at 15 cm burial	total mortality at 16 cm burial		
		reduced growth at 10 cm burial	4 mo. survival of complete burial if	Clarke (1987); Clarke & Kirkman (1989)	Holdfast Bay, SA
	substantial reduction in %cover when		sediment remained aerobic		
	subjected to erosion of 20-25 cm				
			surviving >30 cm burial for 3-4 months	Nelson (1992); Nelson & Paling (in prep.)	WA
	erosion (20-25 cm) led to slow demise			Clarke & Kirkman (1989)	Holdfast Bay, SA
Wave exposure index		2-3 m sign. wave height can dislodge seedlings of Posidonia australis		Ruiz-Montoya et al. (2012)	
		able to withstand 1-1.5 m swell		Van Keulen and Borowitzka (2002)	WA
		prefers shallow sheltered environments		Bryars and Rowling (2009)	SA

Table 3.4 Literature data on critical thresholds for *Posidonia sinuosa*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS
Thresholds (literature values) to determine habitat suitability (HSI)

Species: ***Posidonia sinuosa***

parameter	minimum tolerated	optimum range	maximum tolerated	literature reference	geographic area
sediment composition		occurring from fine to coarse sediments		Van Keulen and Borowitzka (2003)	WA
(%fines)		with variability between sites & seasons			
current velocity					
(cm/sec)					
light regime	7.8 %SI (MLR); or varying 5-12%SI seasonally			DEP (1996)	WA
(%SI)	10% SI (MLR) at canopy level			Masini et al. (1995)	WA
	8.5 %SI (MLR)			Collier (2006) PhD thesis	WA
	8-14 %SI (MLR)			Collier et al. (2007); Masini & Manning (1995)	WA
		82-91% shoot loss at 4-5% shading after 105 d		Collier et al. (2009)	WA
	20 %SI (MLR)	but 24 mo survival at 12% SI		Gordon et al. (1994)	Australia
		30-55% shoot loss at 80-99% shading after 104 d		Gordon et al. (1994)	Australia
	12%SI	meadow collapse if <12% for 2 yrs		Gordon et al. (1994)	WA
	onset mortality after 2 yrs if <10%	at sub-compensation light levels		Gordon et al. (1992)	WA
	reduced growth after 1 yr if <20%				
	24.7 %SI (MLR)			Duarte (1991); Dennison et al. (1993)	Waterloo Bay, SA
	4% SI (surviving meadow at 18m)			Collings et al. (2006)	SA
	10.1 mol photons/m2/d (~17%SI)			Gattuso et al. (2006)	
		Posidonia sinuosa survives longer		Chesire et al. (2001)	
		than Heterozostera tasmanica			
salinity	tolerates prolonged exposure to			Westphalen et al. (2004)	SA
(ppt)	0 ppt (no effects if 72 hrs; initial effects after 4 weeks; mortality after 6 weeks)			Westphalen et al. (2005)	SA
	mortality if exposed 7 weeks to <1 ppt			Bryars & Collins (2008)	SA
	Seedlings / seeds clearly stressed or killed by <10ppt			Bryars & Collins (2008)	SA
temperature	39% decline in photosynthetic	13-24°C (optimum 18-23°C)		Masini et al. (1995)	Princes Royal Harbour
(°C)	rates at 13°C	13-23°C (optimum 18-23°C)		Masini and Manning (1997)	WA
		20.5°C (optimal for photosynthesis)		Lee et al. (2007)	
		14-20°C		Shepherd and Womersley (1981)	Waterloo Bay, SA
low tide exposure	0 (will die if exposed at low tide)				
(h/day)					
sedimentation		less than 10 cm (<30% mortality)	50% shoot loss at 15.4 cm burial	Cabaco et al. (2008)	
(mm)			still 5% survival at 30 cm burial		
			surviving burial for 3-4 months	Nelson (1992)	WA
Wave exposure index		growing at moderate wave exposure		Irving et al. (2010)	SA
		(mean annual significant wave height ~1 m)			

Table 3.5 Literature data on critical thresholds for *Posidonia coriacea*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS					
Thresholds (literature values) to determine habitat suitability (HSI)					
Species:	***Posidonia coriacea***				
parameter	**minimum tolerated**	**optimum range**	**maximum tolerated**	**literature reference**	**geographic area**
sediment composition					
(%fines)					
current velocity					
(cm/sec)					
light regime	8 %SI (MLR)			Duarte (1991); Westphalen et al. (2004)	
(%SI)	3.2 mol photons/m2/d (~5%SI)			Gattuso et al. (2006)	
salinity		35 ppt and above	50 ppt upper limit	Walker et al. (1988)	WA, Shark Bay
(ppt)					
temperature		14-20°C		Shepherd and Womersley (1981)	Waterloo Bay, SA
(°C)		15-20°C (winter min. - summer max.)		Walker (1991)	WA
low tide exposure	0 (will die if exposed at low tide)				
(h/day)					
sedimentation	-4.5 to -8.5 cm erosion led to high losses of transplanted shoots			Paling et al. (2003)	WA
(mm)	(storm events led up to -35 cm erosion events at some sites)				
Wave exposure index		adapted to much higher wave energy environments		Bryars and Rowling (2009)	SA
		than P. angustifolia and P. sinuosa			
		a more robust 'wave-tolerant' species		Koch (ERDC report on waves)	
		a *'swell-tolerant'* species			

Table 3.6 Literature data on critical thresholds for *Posidonia angustifolia*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS					
Thresholds (literature values) to determine habitat suitability (HSI)					
Species:	***Posidonia angustifolia***				
parameter	**minimum tolerated**	**optimum range**	**maximum tolerated**	**literature reference**	**geographic area**
sediment composition					
(%fines)					
current velocity					
(cm/sec)					
light regime	8.5% SI			Collier (2006) PhD thesis	WA
(%SI)	6.1% SI			Duarte (1991)	SA?
	2.4-10.1%SI (MLR); n=2; mean=6.2			Gattuso et al. (2006)	SA?
	24.7 %SI			Duarte (1991); Dennison et al. (1993)	Waterloo Bay, SA
	4% SI (surviving meadow at 18m)			Collings et al. (2006)	SA
salinity	**fruits** sensitive to low S (10 ppt):	75% mortality at 10 ppt (72 h)		Westphalen et al. (2005)	
(ppt)	100% mortality at 0 ppt (72 h)	40% mortality at 20 ppt (72 h)			
		<20% mortality at 34 ppt (72 h)			
	mortality if exposed 7 weeks to <1 ppt			Bryars & Collins (2008)	SA
	Seedlings / seeds clearly stressed or killed by <10ppt			Bryars & Collins (2008)	SA
temperature					
(°C)		14-20°C		Shepherd and Womersley (1981)	Waterloo Bay, SA
low tide exposure	0 (will die if exposed at low tide)				
(h/day)		dominates in deeper parts over other Posidonia spp.		Bryars and Rowling (2009)	SA
sedimentation	complete burial (60 cm) reduced			Clarke (1987)	
(mm)	growth but no mortality after 4 mo				
	(if anaerobic, mortality within 2 wk)				
Wave exposure index					

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Table 3.7 Literature data on critical thresholds for *Heterozostera tasmanica*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS
Thresholds (literature values) to determine habitat suitability (HSI)

Species: ***Heterozostera tasmanica***

parameter	minimum tolerated	optimum range	maximum tolerated	literature reference	geographic area
sediment composition		2.8 - 30.9 % fines found in healthy meadows		Edgar and Shaw (1995)	
(%fines)		(with 2.6-5.3% organics)			
current velocity					
(cm/sec)					
light regime	2 - 7.2 %SI (MLR)			Duarte (1991)	SA?
	0.7-8.2 %SI (MLR); n=8; mean=2.9%			Gattuso et al. (2006)	
(%SI)	2-9 %SI (MLR)			Bulthuis (1983); Campbell et al. (2003)	VIC
	9 %SI (MLR)	10 mo survival at 9% SI; 2-4 mo survival at 2% SI		Bulthuis & Woelkerling (1983)	VIC
	5% SI (MLR)			Warry & Hindrell (2009)	VIC
	5-13 %SI (MLR)	mortality after 3 mo. if exposed to <5% SI		Kirkman et al. (2012); Bulthuis (1983)	VIC
	4.4 %SI (MLR)			Duarte (1991); Dennison et al. (1993)	Spencer Gulf, SA
	17.4%SI (MLR)			Duarte (1991)	
	20.2 %SI (MLR)			Dennison et al. (1993)	Waterloo Bay, VIC
	24.7 %SI (MLR)			Duarte (1991)	(Waterloo Bay, Australia)
	5 %SI (MLR)			Dennison et al. (1993)	VIC
	5 %SI (MLR)			Bulthuis (1983)	Port Philip Bay, VIC
	mean: 10.4 %SI			Lee et al. (2007)	
salinity	tolerated prolonged exposure to	can occur in estuaries		Westphalen et al. (2004)	SA
(ppt)	15 ppt for 3 months				
		healthy meadow growing at 33-38 ppt in Western Port, VIC		Edgar et al. (1994)	VIC
temperature		30 °C (optimum)		Bulthuis (1987); Lee et al. (2007)	VIC
(°C)		5-40°C (optimum 30°C)		Bulthuis (1983)	VIC
		healthy meadow growing at 10-22 °C in Western Port, VIC		Edgar et al. (1994)	VIC
		14-20°C		Shepherd and Womersley (1981)	Waterloo Bay, SA
low tide exposure	can tolerate exposure at low tide	can occur in intertidal		Robertson (1984)	SA
(h/day)		typically occurs subtidally to 3-4 m deep (depending on turbidity)		Warry & Hindrell (2009)	VIC
	transplants unable to survive significant desiccation in intertidal where Zostera muelleri thrived			Clarke & Kirkman (1989)	Western Port, VIC
sedimentation	vulnerable to sediment deposition			Clarke and Kirkman (1989)	
(mm)	due to coating of leaves (esp. in the intertidal)				
Wave exposure index		only forms meadows of significant extent in		Clarke & Kirkman (1989)	Holdfast Bay, SA
		shallow *low wave action* areas			
		often found in blow-outs			

Table 3.8 Literature data on critical thresholds for *Zostera muellerii*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS
Thresholds (literature values) to determine habitat suitability (HSI)

Species: ***Zostera muellerii (= Z. capricorni)***

parameter	minimum tolerated	optimum range	maximum tolerated	literature reference	geographic area
sediment composition		0.5 - 72 % found in healthy beds		Edgar and Shaw (1995)	SA
(%fines)		inhabits muddy estuarine areas		Collier et al. (2011)	QLD
		dominates when higher %fines		McKenzie (2007)	
current velocity		<0.5 m/sec	(>0.5 m/sec??)	Schwarz et al (2005)	New Zealand
(cm/sec)					
light regime	16-36 %SI (MLR)			Longstaff (2002)	QLD
(%SI)	30 %SI (MLR)			Longstaff et al. (1999)	Moreton Bay
	30 %SI (MLR)			Abal & Dennison (1996)	Moreton Bay
		optimum: 40% SI (conservative estimate)		Schwarz et al. (2005)	New Zealand
	only 1 month survival at 5 %SI			Grice et al. (1996)	
	survival of 3 days complete shading, but loss of epiphytes			Kirkman (1978)	tanks
salinity	tolerant to low salinity (even 0 ppt for a few hrs)			Shepherd and Robertson (1989)	SA
(ppt)		lower seed germination at 22 than 32 ppt (aerobic)		Brenchley & Probert (1998)	EA
		can occur in estuaries		Westphalen et al. (2004)	SA
		found growing in salinities of 3-37 ppt		Tyerman (1989)	Illawara Lake NSW
	0 ppt	35 ppt	140 ppt	Kerr & Strother (1985); Touchette (2007)	
	10 ppt (long-term); <10 ppt (short-term)		40 ppt (long-term)		
	9.5 ppt		33.5 ppt	McKenzie (1994)	QLD
		healthy meadow growing at 33-38 ppt in Western Port, VIC		Edgar et al. (1994)	VIC
temperature		19-30 °C	severe stress at 33°C	Collier et al. (2011)	QLD
(°C)			drastic decline at 35°C & above	Campbell et al. (2006)	QLD
			>30 °C (declining productivity)	Fong & Harwell (1994)	Australia
		20-33 °C		McKenzie (1994)	QLD
		healthy meadow growing at 10-22 °C in Western Port, VIC		Edgar et al. (1994)	VIC
low tide exposure	can tolerate exposure at low tide	can occur in intertidal		Robertson (1984)	SA
(h/day)	less than 1 h exposure (low light)	optimal: 2-5 h exposure	more than 6 h exposure	Schwarz et al (2005)	New Zealand
		0 - 6895 min / month		McKenzie (1994)	QLD
		mainly occupies intertidal areas		Warry & Hindrell (2009)	VIC
		mainly intertidal		Bryars & Rowling (2009)	SA
	very tolerant of intertidal exposure, thriving on intertidal mudbanks			Clarke & Kirkman (1989)	Western Port, VIC
	able to tolerate long periods of low tide exposure				
sedimentation	sensitive to burial & sedimentation			Seddon (2000)	SA
(mm)			(10 cm caused total loss)	Waycott et al. (2007)	QLD
Wave exposure index		no data			

Table 3.9 Literature data on critical thresholds for *Halophila australis*

SEAGRASS HABITAT MODEL - ADELAIDE COASTAL WATERS
Thresholds (literature values) to determine habitat suitability (HSI)

Species: ***Halophila australis***

parameter	minimum tolerated	optimum range	maximum tolerated	literature reference	geographic area
sediment composition		occurs on finer silts and muds		Warry & Hindrell (2009)	VIC
(%fines)		often associated with soft, fine sediments		Roob et al. (1998)	VIC
		colonizer of bare sand disturbed by dredging		Bryars and Rowling (2009)	SA
current velocity		persisting mainly in understory of the larger		Ruiz-Montoya et al. (2012)	WA
(cm/sec)		Posidonia meadows or as isolated patches			
light regime	2,5 %SI	*Halophila decipiens*		Dennison (1987)	Hobe Sound, Florida, USA
(%SI)	3% SI	*Halophila stlpulacea*		Beer and Waisel (1982)	Gulf of Eilat, Red Sea
(using other *Halophila* spp.	4.4 %SI	*Halophila decipiens*		Williams and Dennison (1990)	St.Croix, Caribbean
as proxy)	5 %SI	*Halophila* spp.		Dennison et al. (1993)	Sub tropical seas
	8.8 %SI	*Halophila decipiens*		Duarte (1991)	Northwest Cuba
	16 %SI	*Halophila ovalis*		Schwarz et al. (2000)	Zanzibar, Tanzania
salinity		less tolerant to low salinities than Zostera muellerii		Tyerman (1989)	Australia
(ppt)					
	Halophila ovalis:				
	survives several months of 15-20 ppt	optimum: 25-35 ppt	tolerates up to 45 ppt	Hillman & McComb, 1988 (a, b)	Swan River estuary, WA
	die-back when <10 ppt >4 months due to heavy river discharge				
	Marine *H. ovalis:* intolerant of prolonged exposure to low salinity (20%), with 75% mortality within 3 wks			Benjamin et al. (1999)	
	Estuarine *H. ovalis:* healthy at 20 ppt, growing well at 10 ppt but stressed after 4 weeks				
temperature			>30 °C (declining productivity)	Fong & Harwell (1994)	Australia
(°C)		14-20°C		Shepherd and Womersley (1981)	Waterloo Bay, SA
low tide exposure					
(h/day)					
sedimentation			4 cm burial (Halophila ovalis)	Ooi et al. (2011)	WA
(mm)			(nearly full mortality at 8 cm burial)		
			full burial not survived >1 wk	Clarke & Kirkman (1989)	Holdfast Bay, SA
			but rapid coloniser in areas with high siltation (between perturbations)		
Wave exposure index		2-3 m sign. wave height can dislodge seedlings of *Halophila ovalis*		Ruiz-Montoya et al. (2012)	
		often found in blow-out areas (along with Heterozostera tasmanica)			
		occurs in deeper (> 2-3 m depth) waters,		Roob et al. (1998)	VIC
		often growing in association with *Heterozostera*		Warry & Hindrell (2009)	VIC
		at deeper margins of *Heterozostera* distribution			

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