



## Water for a Healthy Country

# Changes in the distribution and abundance of *Ruppia tuberosa* in the Coorong

Daniel J Rogers and David C Paton

June 2009



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## Changes in the distribution and abundance of *Ruppia tuberosa* in the Coorong

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## Foreword

The environmental assets of the Coorong, Lower Lakes and Murray Mouth (CLLAMM) region in South Australia are currently under threat as a result of ongoing changes in the hydrological regime of the River Murray, at the end of the Murray-Darling Basin. While a number of initiatives are underway to halt or reverse this environmental decline, rehabilitation efforts are hampered by the lack of knowledge about the links between flows and ecological responses in the system.

The CLLAMM program is a collaborative research effort that aims to produce a decision-support framework for environmental flow management for the CLLAMM region. This involves research to understand the links between the key ecosystem drivers for the region (such as water level and salinity) and key ecological processes (generation of bird habitat, fish recruitment, etc). A second step involves the development of tools to predict how ecological communities will respond to manipulations of the “management levers” for environmental flows in the region. These levers include flow releases from upstream reservoirs, the Lower Lakes barrages, and the Upper South-East Drainage scheme, and dredging of the Murray Mouth. The framework aims to evaluate the environmental trade-offs for different scenarios of manipulation of management levers, as well as different future climate scenarios for the Murray-Darling Basin.

One of the most challenging tasks in the development of the framework is predicting the response of ecological communities to future changes in environmental conditions in the CLLAMM region. The CLLAMMecology Research Cluster is a partnership between CSIRO, the University of Adelaide, Flinders University and SARDI Aquatic Sciences that is supported through CSIRO’s Flagship Collaboration Fund. CLLAMMecology brings together a range in skills in theoretical and applied ecology with the aim to produce a new generation of ecological response models for the CLLAMM region.

This report is part of a series summarising the output from the CLLAMMecology Research Cluster. Previous reports and additional information about the program can be found at <http://www.csiro.au/partnerships/CLLAMMecologyCluster.html>

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Additional funding and support for the long-term monitoring of the Coorong used in this report was provided by Earthwatch (Australia) and its Research Corp, the SA Department for Environment and Heritage, the SA Department of Water, Land and Biodiversity Conservation and Nature Foundation South Australia. The SA Department for Environment and Heritage provided research permits for work in the Coorong and Lower Lakes (C13897 and Y25372). Research involving vertebrate fauna was covered by a University of Adelaide Animal Ethics Approval (S-077-2006).

## Executive Summary

In recent history, *Ruppia tuberosa* has spatially dominated the submerged aquatic vegetation of the South Lagoon of the Coorong. The species is considered to play a central role in the Coorong's ecology, particularly as a food source for waterbirds and habitat for invertebrates and fish. An understanding of the spatiotemporal dynamics of *R. tuberosa*, and the hydrological factors that might drive these dynamics, will thus help to identify key drivers for the broader ecological dynamics in the Coorong and assist in the development of predictive models.

This report summarises the results of historic monitoring of *R. tuberosa* in the Coorong, collected since 1998. Three components of *R. tuberosa* ecology were monitored: 1) Winter propagule and shoot abundance; 2) Winter cover and shoot density; 3) Summer propagule abundance. These three monitoring programs were undertaken using different methods and over different spatial scales, as the original objectives of these programs also differed. However, the trends for all three were similar. Winter shoot cover and density have declined across the South Lagoon of the Coorong since 1999, and no shoots were recorded from any of the four sites in 2008. The nature of these declines was also spatially explicit, with declines in cover being more temporally advanced in the south than the north of the South Lagoon. This suggests a range contraction from south to north for *R. tuberosa* in the South Lagoon. Conversely, *R. tuberosa* shoots were first recorded further north in the North Lagoon (at Noonameena, ~21 km north of Parnka Point) in 2005, and *R. tuberosa* appears to be slowly increasing in distribution and abundance in the North Lagoon. .

Measures of propagule abundance showed similar spatiotemporal patterns, with the propagule banks declining over time for the South Lagoon. These propagule banks consisted of seeds and turions, with turions accounting for 47-82% of all propagules in January from 2001-2006, but only 15% and 3% in 2007 and 2008 respectively. This is consistent with turions being short-lived. At present no *Ruppia tuberosa* plants appear to be able to establish from the current seed-dominated propagule banks in the South Lagoon, possibly because many of the seeds are not viable or are buried too deep in the sediments. Further work on the composition and dynamics of the propagule banks of *R. tuberosa* in the Coorong are required. Turions appear more important than seeds for dispersal, since turions and not seeds, were detected at sites like Noonameena up to six months before the first shoots were detected.

The current distribution of *R. tuberosa* was determined at a fine-scale (~ every 3 km) using recent historic distributions as a guide. This survey confirmed the absence of *R. tuberosa* from the South Lagoon, with the southernmost records of shoots coming from Parnka Point at the junction of the North and South Lagoons. In July 2008, the highest densities of *R. tuberosa* shoots were found between 'The Needles' (~ 6 km north of Parnka Point) and Noonameena. Shoots were also recorded at low densities at Long Point, 31 km north of Parnka Point, suggesting the continued range expansion of this species into the North Lagoon.

Preliminary analyses of the hydrological drivers for these historic changes were based on the hydrological models of Webster (2005), and used a statistical technique called Nonparametric Multiplicative Regression (NPMR). The best candidate model using this technique ( $xR^2 = 0.637$ ) found that a combination of three salinity variables and one generic water level variable best explained changes in the distribution of *R. tuberosa* in the Coorong. However, when these results were compared with the current distribution of *R. tuberosa*, the model failed to predict the rapid northern expansion of the species into the North Lagoon, although the South Lagoon decline was well predicted.

Given the significant role of *R. tuberosa* in the Coorong ecosystem, and its predicted sensitivity to hydrological changes, a more robust modelling approach is required to accurately predict the responses of this species to future Coorong environments. While the regression techniques described here may continue to prove useful, they are correlative and not causative. Future work should document the the responses of *R. tuberosa* to its physical (hydrological) and biotic environment and incorporate these responses directly into the models.

# 1. Introduction

Submerged aquatic macrophytes play an extremely important determining role in the structure and function of wetland ecosystems (Carpenter and Lodge 1986). One of these is their role in structuring planktonic communities, through changes in the physical environment, competition for nutrients, and creation of habitat for zooplankton that graze on phytoplankton (van Donk and van de Bund 2002). In addition, submerged aquatic macrophytes provide important habitats and resources for higher aquatic organisms. These functions include as substrate for fish egg deposition (Treasurer 1981; Poncin *et al.* 1996), decreased predation risk for zooplankton and small fish (Eklöv and Persson 1996; Grimm and Backx 1990), and a direct and indirect (through their role in supporting lower trophic level organisms) food source for fish (Grenouillet and Pont 2001; Bickel and Closs 2008) and aquatic birds (Percival *et al.* 1996; Bortolus *et al.* 1998; Schmieder *et al.* 2006). The pervasive effect of submerged macrophytes across multiple trophic levels means that their role in structuring aquatic ecological communities can be fundamental (Hanson and Butler 1994).

The hypersaline conditions that dominate much of the Coorong have restricted the submerged macrophyte diversity to two key species. *Ruppia tuberosa* has historically been recorded along the length of the Coorong South Lagoon, while a second *Ruppia* species (*R. megacarpa*) was historically found in the Coorong North Lagoon, concentrated particularly in the estuarine regions of the system (Nicol 2005). As with other macrophyte-dominated shallow wetlands, *Ruppia* spp have historically played an important role in the structure and function of the Coorong wetland ecosystem. In the Coorong South Lagoon, *R. tuberosa* plays a role in modifying the physical environment (particularly by modifying water velocity) and biogeochemical processes (e.g. competition with phytoplankton for nutrients). Primarily, however, *R. tuberosa* in the Coorong provides critical habitat and food resources for higher trophic organisms (fish and birds; Phillips and Muller 2006). This includes its central role as a direct food resource for a range of aquatic birds, including Black Swan *Cygnus atratus* (that forage on shoots and turions), and a number of migratory shorebird *Calidris* species, that forage on asexual (turions) and sexual (seeds) propagules (Paton 2005). Strong links between *Ruppia* productivity and bird (particularly waterfowl) abundance have been recorded elsewhere (cited in Kantrud 1991), to the extent that the common name for *Ruppia* species ('widgeongrass') reflects their importance in duck diets. In addition, successful recruitment of the saline-tolerant Smallmouth Hardyhead *Atherinosoma microstoma* may be dependent on the presence of *R. tuberosa*, by providing egg deposition sites in an otherwise soft-sediment environment. *Ruppia tuberosa* thus plays an important role in maintaining key ecological values in the Coorong, particularly those for which the wetlands are held in international regard (e.g. Ramsar; DEH 2000).

Given the central role that *R. tuberosa* has played in the Coorong South Lagoon ecosystem, an understanding of the response of this key species to environmental change is fundamental to understanding the function of the whole ecosystem. The results presented in this report aim to primarily improve our understanding regarding the responses of *R. tuberosa* to environmental (particularly hydrological) change. We first present the results of historic monitoring programs for *R. tuberosa* in the Coorong, thereby describing the spatiotemporal changes that have occurred in the distribution of the species. We then use these data, coupled with the outputs of a hydrological model for the Coorong (Webster 2005), to develop a predictive response model for *R. tuberosa* in the Coorong, that can be used to predict future changes in the distribution of the species to alternative environmental scenarios.

## **2. Methods**

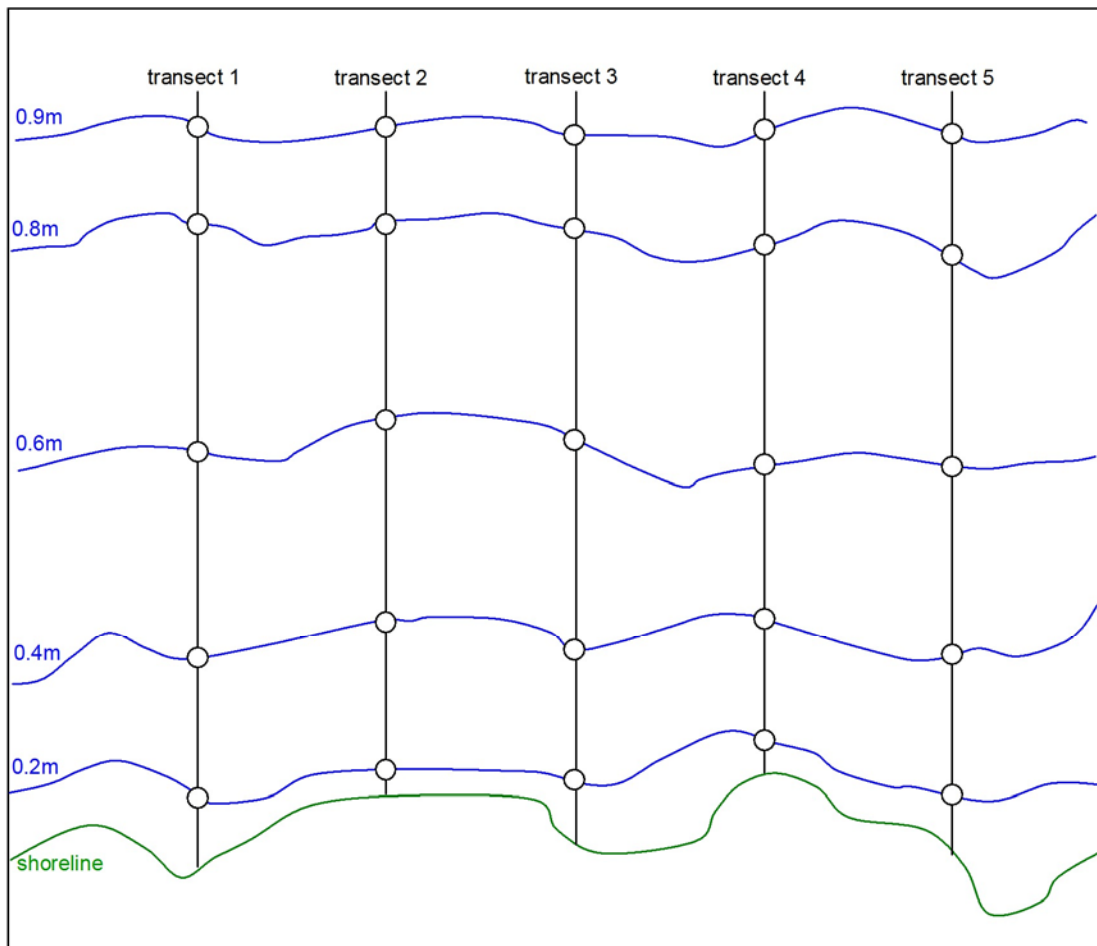
### **2.1. *Ruppia tuberosa* Surveys**

Three survey methods were used to determine the distribution and abundance of *Ruppia tuberosa* in the Coorong: 1) Annual Winter (July) surveys of *R. tuberosa* shoots, seeds and turions; 2) Annual Winter (July) surveys of *R. tuberosa* above-ground cover; 3) Annual Summer (January) surveys of *R. tuberosa* shoots, seeds and turions. Combinations of these variables were then used as the response variables in subsequent Non-parametric Multiplicative Regression (NPMR) models.

#### **2.1.1. Annual Winter Survey (Shoots, seeds and turions)**

At each survey site, five parallel transects, 25m apart and running perpendicular from the shoreline, were established (Figure 1). Along each transect, two sediment cores (7.5 cm  $\varnothing$  x 4cm depth) were collected at each of the following water depths: 0.2m, 0.4m, 0.6m, 0.8m and 0.9m. At each site, therefore, 50 cores were collected (2 cores x 5 depths x 5 transects). Each sample was subsequently sieved through a 500 $\mu$ m Endecott sieve, and all *R. tuberosa* seeds, turions and shoots were counted. Water level was also measured every 50m along each transect, up to a depth of 0.9m. The length of each transect was thus determined by the distance from the shore at which the water depth was 0.9m or greater.

Winter surveys for shoots, seeds and turions were conducted at five sites (Tea-tree Crossing, Salt Creek, Policeman Point, Villa dei Yumpa, and Noonameena; Figure 2) annually in July between 1998 and 2008. Additional annual winter surveys were conducted at three sites (Tea-tree Crossing, Policeman's Point and Villa dei Yumpa) between 1990 and 1992.



**Figure 1. A hypothetical map showing the layout of each *R. tuberosa* transect grid. The green line represents the shoreline at a site, while the blue lines represent the water depth contours at a site. Five parallel transects (black lines) were run perpendicular from the shoreline, and two core samples were taken at the points at which each of these transects intersect with each of the depth contours shown (represented by open circles).**

### 2.1.2. Annual Winter Survey (*R. tuberosa* Cover)

Using the transect grid described above, 50 core samples (7.5 cm  $\varnothing$  x 4cm depth) were collected between each neighbouring pair of transects (i.e. between transects 1 and 2, transects 2 and 3, transects 3 and 4, and transects 4 and 5), between 0.4m and 0.7m water depth. A total of 200 cores were thus collected at each site. The number of shoots detected in each core was counted *in situ*. Both the percentage of cores in which *R. tuberosa* shoots were detected, and the mean number of shoots per core were calculated for each site. This method provided a more sensitive measure for spatiotemporal changes in *R. tuberosa* cover than the method described in 2.1.1, although without the same level of biological detail provided by counting *R. tuberosa* seeds and turions.

Winter surveys for *R. tuberosa* cover were conducted at five sites (Tea-tree Crossing, Salt Creek, Policeman Point, Villa dei Yumpa, and Noonameena; Figure 2) annually between 1999 and 2008.

### 2.1.3. Annual Summer Survey (Shoots, seeds and turions)

Summer surveys for *R. tuberosa* were principally conducted in order to assess food availability for migratory shorebirds. At each sampling site, ten core samples (core size: 7.5 cm  $\varnothing$ , 4 cm

deep) of surface mud were collected at each of three locations relative to the waterline (total core samples per site = 30). These locations were: 1) at a water depth of 0.3m; 2) at the waterline; 3) midway between the waterline and the high water mark (i.e. exposed mud). The 30 core samples were then sifted through a 500µm Endecott sieve, and the number of *R. tuberosa* shoots, seeds, and type I and type II turions counted for each core sample, in addition to the number of *Tanytarsus barbitarsus* (Chironomidae) larvae and pupae, and polychaetes. Sample sizes were increased to 25 core samples per location (75 per site) from January 2007 because of significant reductions in the abundances of *Ruppia*.

Summer surveys were conducted at 17 sites along the entire length of the Coorong (Figure 2). As suggested above, the reason for conducting the survey beyond the historic and predicted range of *R. tuberosa* in the Coorong was because these surveys were assessing food availability for shorebirds (across all major food items), not just the distribution and abundance of *R. tuberosa*. However, the extent of this survey allows for a broader assessment of the extent of *R. tuberosa* in the Coorong than can be understood from the winter surveys alone. Summer surveys were conducted annually in January between 2001 and 2008, with additional surveys conducted for sites in the South Lagoon in January 1985, January 1991 and January 1992.

#### **2.1.4. Survey of Current Distribution**

A one-off survey was conducted in July 2008, to obtain greater detail regarding the current distribution of *R. tuberosa* in the Coorong. In addition to providing information on the current distribution of *R. tuberosa*, these data were also used to validate the model developed using Hyperniche (see below). Because the annual winter surveys described in 2.1.1 and 2.1.2 were done at a relatively coarse spatial resolution (5 sites for the entire South Lagoon and southern North Lagoon – average of one site per 15 km), this one-off survey was conducted at a finer spatial resolution. The sampling distribution encompassed the known current distribution of *R. tuberosa* in the Coorong. Sites were chosen by selecting and sampling from a site within the core of the known distribution, and then sampling at sites approximately 3km north or south of this core site. New sites were continuously added (moving ~3km between sites) until *R. tuberosa* was not recorded at a site. In some cases, a distance of greater than 3km separates neighbouring sites, due to poor access to closer neighbouring sites.

Using this method, thirteen sites were sampled along a 45km section of the Coorong (Figure 3). At each site, 50 core samples (core size: 7.5cm ø, 4cm deep) were taken from a depth of between 0.5m and 0.8m, and the numbers of shoots detected in each core sample were counted. As with 2.1.2 above, both the percentage of cores in which *R. tuberosa* shoots were detected, and the mean number of shoots per core, were calculated for each site.

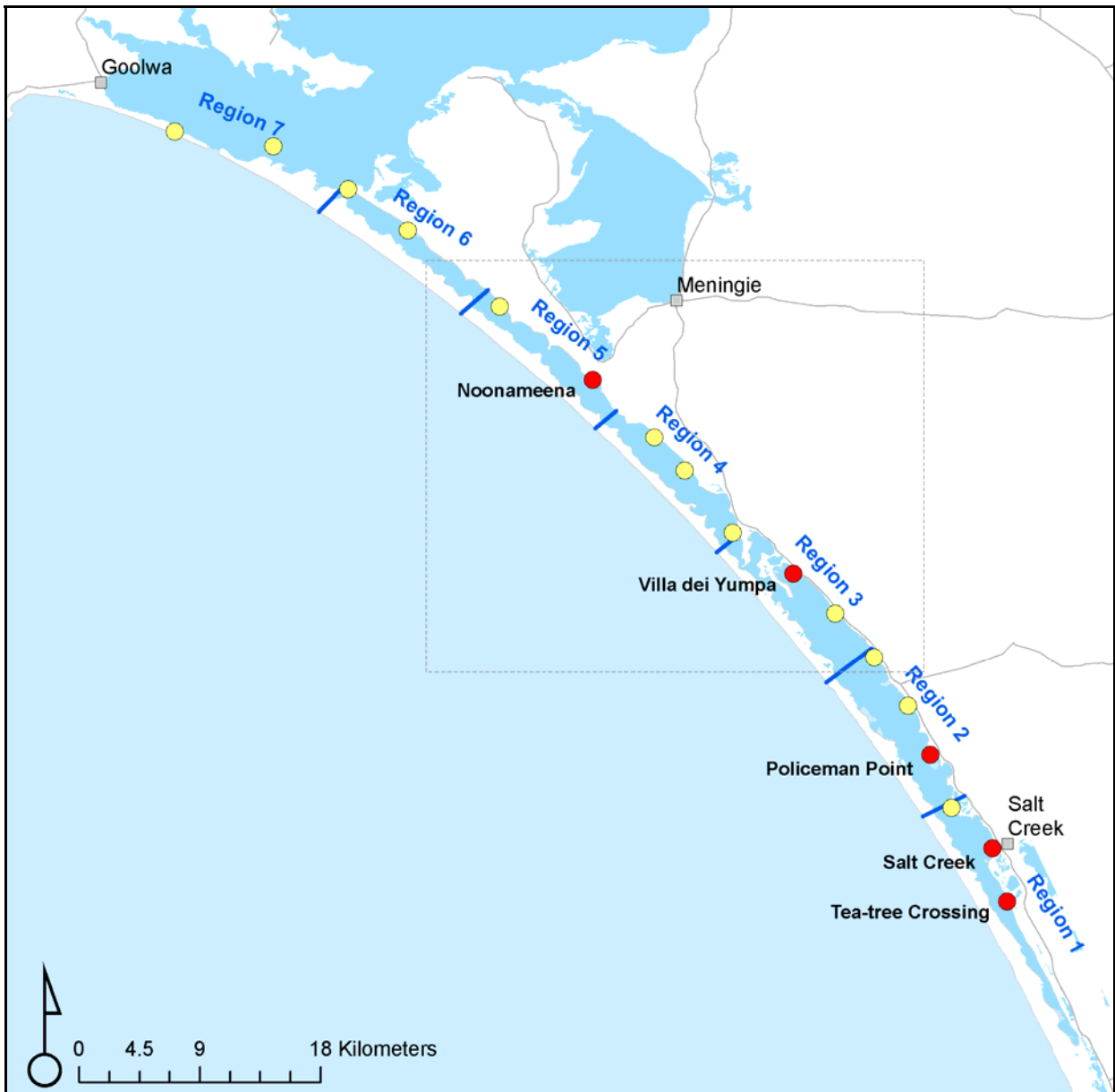
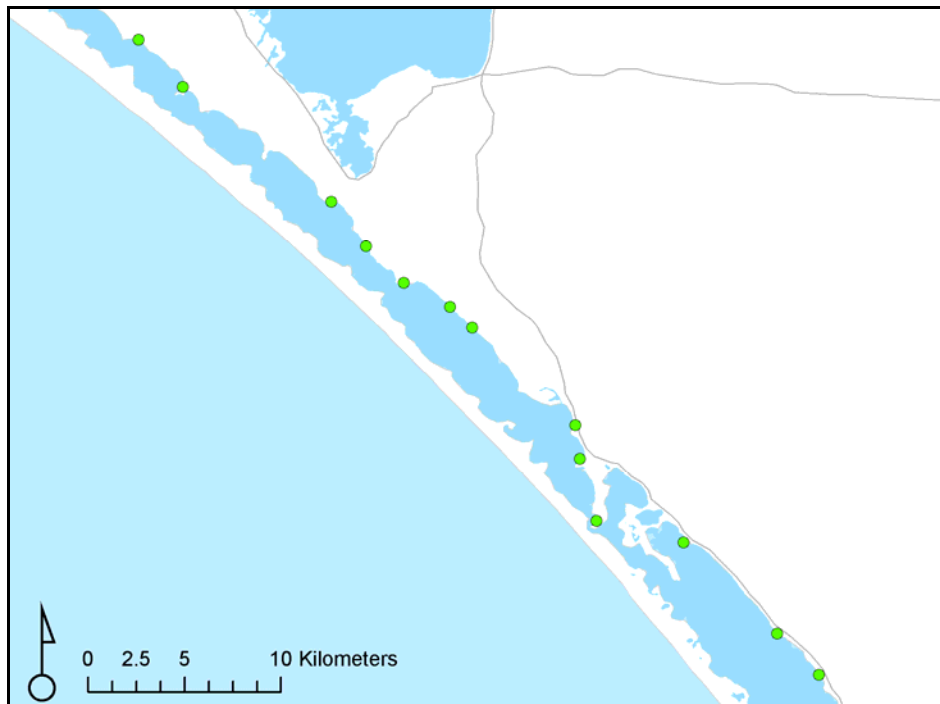


Figure 2. Map of the Coorong, showing annual survey sites. Sites in yellow were surveyed annually in January only (using the methods described in Section 2.1.3), while sites in red were surveyed annually in January (2.1.3) and July (using the methods described in Sections 2.1.1 and 2.1.2). The regions referred to in Results 3.1.2 are presented in blue. The hashed box shows the extent of the current distribution survey (see Figure 3).



**Figure 3. Map showing the location of the 13 sites sampled in July 2008 (as described in 2.1.4). See Figure 2 inset for the location of this area within the Coorong region.**

## 2.2. Analyses

### 2.2.1. Collation of explanatory and response variables

For the NPMR analysis presented here, we defined *R. tuberosa* habitat by the percent of cores containing shoots in winter (July) of any year. This definition inherently assumes that the entire Coorong wetland is available as habitat for *R. tuberosa*, and does not account for issues related to the distribution of source populations or dispersal limitation (see Discussion). From the survey data, the following variable was used as the response variable in the NPMR analysis (see below):

**PCORES:** The percent of cores that contained *R. tuberosa* shoots. These data were drawn from the annual winter survey for *R. tuberosa* cover (section 2.1.2).

Data for the explanatory variables used in the NPMR analysis were drawn from the 1-D hydrodynamic model of the Coorong developed by Webster (2005). This model predicts daily salinity ( $\text{gL}^{-1}$ ) at 14 points along the Coorong between the Murray Mouth and Tea-tree Crossing, and hourly water level (metres relative to AHD) at 105 points. The following explanatory variables were used in the NPMR analysis:

**X SAL:** The mean salinity for the period May 1 to November 30, in the calendar year prior to measurement of the response variable (for example, for *R. tuberosa* samples measured in 2000, X SAL is given as the mean salinity for the period May1 to November 30, 1999). Mean salinity was calculated as the average of daily average salinity for each site in each year.

MAM SAL: The maximum monthly average salinity for the period from May 1 to November 30, in the calendar year prior to measurement of the response variable. Maximum monthly average salinity was calculated as the maximum of the monthly averages of daily average salinity.

MIM SAL: The minimum monthly average salinity for the period from May 1 to November 30, in the calendar year prior to measurement of the response variable. Minimum monthly average salinity was calculated as the minimum of the monthly averages of daily average salinity.

LD20: The last day on which the daily average water level was greater than 0.2m AHD. The 'last day' is defined as the last date of a continuous series of dates (>14 days) with daily average water levels of greater than 0.2m AHD, that do not contain blocks of more than 7 days with daily average water levels of less than 0.2m AHD. If a series of greater than 7 days with daily average water levels less than 0.2m AHD was encountered, LD20 was defined as the last day immediately prior to this series.

AHD.DAYS: The sum of daily average water levels for each day of the calendar year. This statistic represents the area under the water level time-series curve (e.g. Figure 4) for a calendar year. This statistic provides an indication of the extent of mudflat that is inundated for a unit of time, in the absence of specific bathymetric / topographic information for the sites. Samples with high values for AHD.DAYS, therefore, have a high proportion of mudflats inundated, or have mudflats inundated for long periods, or both.

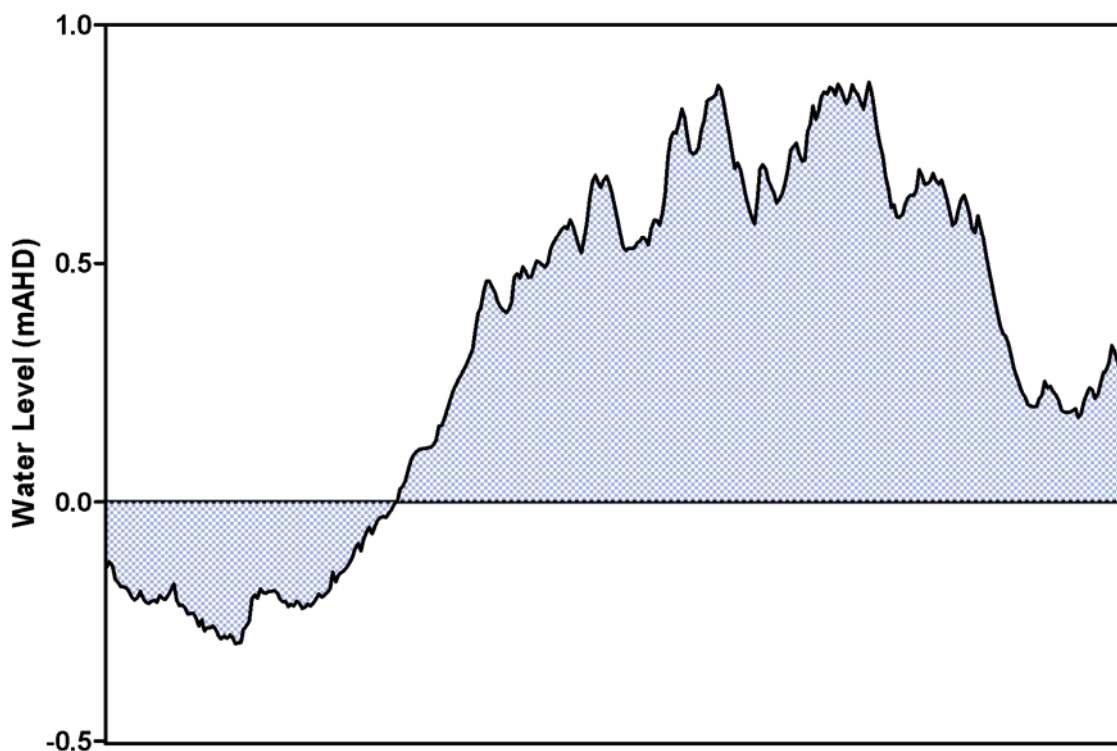


Figure 4. Daily average water level at Policeman Point in 2000. The statistic 'AHD.days' is equal to the area shaded in blue. The area that falls below the X-axis (0 mAHD) is subtracted from the area in blue above the X-axis to give the total value.

## 2.2.2. NPMR Analysis

Using the explanatory and response variables described above, Non-parametric Multiplicative Regression (NPMR) was performed to determine which variables (or combination of variables) best explained spatiotemporal variation in *R. tuberosa*. A Gaussian weighting function was used, with a local mean estimator in a forward stepwise regression. A Gaussian distribution assumes a continuous smooth response to an environmental variable and was used in this modelling since there was no evidence of the existence of critical thresholds above or below which a step wise response by *R. tuberosa* might occur (Nicol 2005). The range of candidate models were evaluated using  $xR^2$  (McCune 2006).  $xR^2$  is calculated by excluding each data point from the basis for the estimate of the response at that point; consequently,  $xR^2$  can be negative (unlike the traditional  $R^2$ ) if the residual sum of squares exceeds the total sum of squares. NPMR was performed using the Hyperniche software package (McCune and Mefford 2004).

## 3. Results

### 3.1. Historic Changes

Changes in the distribution and abundance of *R. tuberosa* in the Coorong are presented in two parts: 1) changes in the distribution and abundance of above-ground shoots; 2) changes in the distribution and abundance of propagules (seeds and turions). These analyses are based on the collation of data from the different survey methods described above.

#### 3.1.1. Changes in *R. tuberosa* cover and density

Since regular annual surveys began in 1998, significant changes have occurred in the distribution and abundance of *R. tuberosa* above-ground shoots (Figure 5, Figure 6). These changes were also spatially-explicit, with declines in *R. tuberosa* density and cover occurring earlier in the southernmost sites than northern South Lagoon sites. *Ruppia tuberosa* shoots were last recorded at Tea-tree Crossing and Salt Creek in 2004, at Policeman Point in 2005, and at Villa dei Yumpa in 2007. The observed pattern of staged extinction from south to north suggests a range contraction for *R. tuberosa* in the South Lagoon of the Coorong. Conversely, *R. tuberosa* was first recorded at Noonameena in 2005, suggesting recent range expansion into the North Lagoon.

#### 3.1.2. Changes in *R. tuberosa* propagule bank (seeds and turions)

Changes in the distribution and abundance of *R. tuberosa* propagules (seeds and turions) was assessed using annual summer sampling described in section 2.1.3. For simplicity of presentation, the abundance of *R. tuberosa* propagules at each of the 17 sites surveyed was summed within the regions described in Figure 2. These arbitrary regions have also been used in the past to describe spatiotemporal changes in the Coorong's waterbird community (Rogers and Paton 2009; Paton *et al.* 2009a). However, site selection for sampling *R. tuberosa* propagules was not based on this regional delineation, and as such the number of sites within each region is not equal. Variance in the number of sites per region is small with all regions having at least two and a maximum of three sites. Consequently, the number of core samples taken within a region in any year also varied (Table 1), primarily due to the number of sites

found within each region, but also due to changes in the sampling methodology between 1985, 1991-2 and 2001-8.

**Table 1. Number of cores of mud taken within each region and year, for the measurement of *R. tuberosa* propagules. The numbers in parentheses after each region refers to the number of sites (for the period 2001-2008). <sup>1</sup> - In 1985, data were collected from 4, 3 and 2 sites for regions 1, 2 and 3 respectively. <sup>2</sup> – In 1991 and 1992, data were collected from one site in each of the three regions.**

Region	Year										
	1985 <sup>1</sup>	1991 <sup>2</sup>	1992 <sup>2</sup>	2001	2002	2003	2004	2005	2006	2007	2008
1 (3)	330	25	25	270	110	90	120	90	120	225	225
2 (3)	240	25	25	90	100	90	110	130	90	225	225
3 (2)	165	25	25	60	70	60	70	110	60	150	150
4 (3)	-	-	-	90	110	90	90	90	90	225	225
5 (2)	-	-	-	60	70	60	60	60	60	150	150

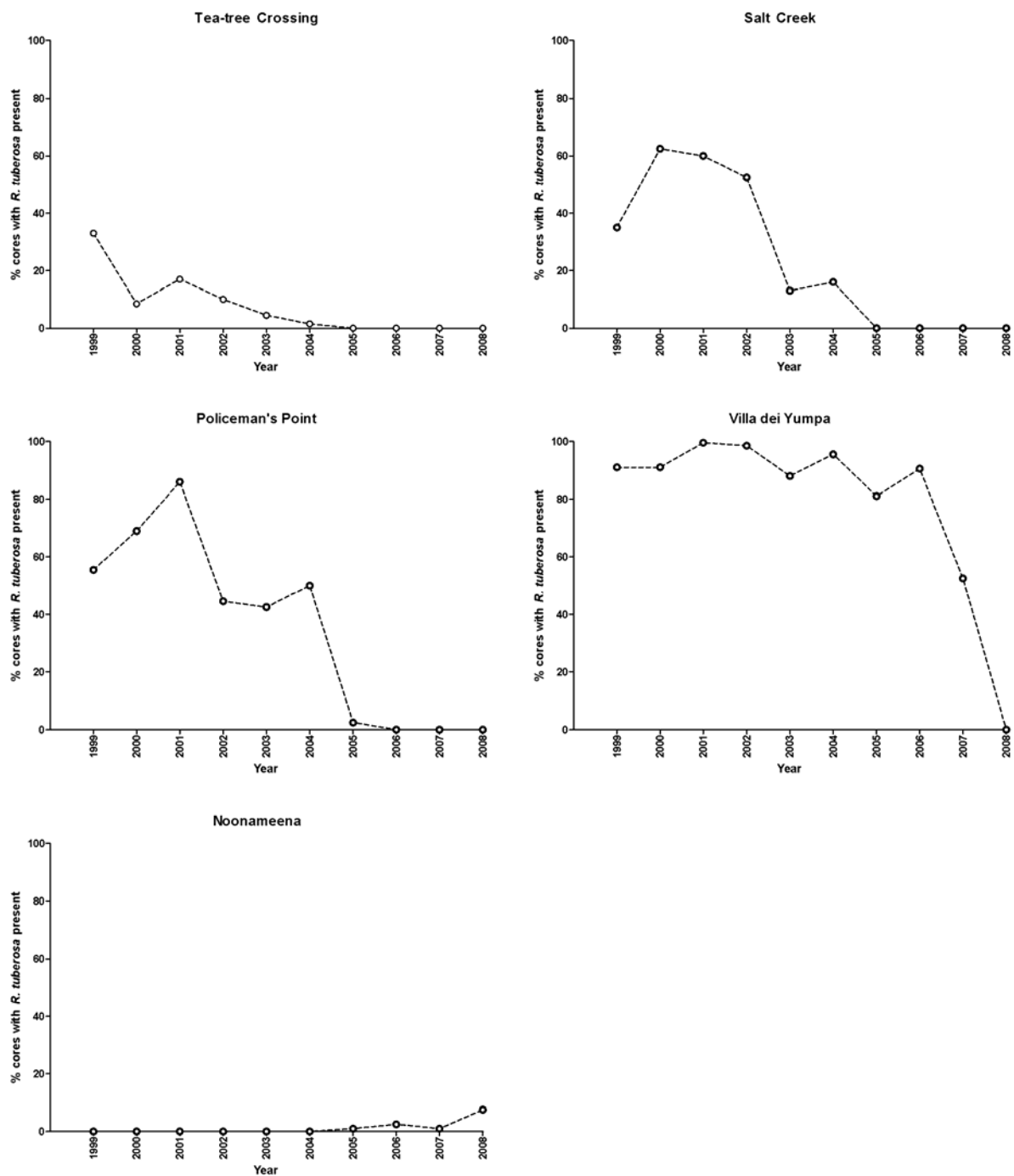
The mean abundance of propagules per core recorded in regions 1 to 5 in each sampling period are presented in Figure 7. Only regions in the South Lagoon were sampled in January 1985, January 1991 and January 1992.

As with winter shoot cover and density, significant spatiotemporal changes have been recorded in the propagule density of *R. tuberosa*. For all three South Lagoon regions, a decline in propagule density has been observed between 2001 and 2008, although *R. tuberosa* propagules were still recorded within all three regions in 2008 (region 1:  $0.21 \pm 0.04$  propagules/core; region 2:  $0.41 \pm 0.26$  propagules/core; region 3:  $5.4 \pm 1.0$  propagules/core). A similar pattern of decline was also recorded in Region 4 (the southernmost region of the North Lagoon), within which no winter survey sites were located. Propagule densities in the northern regions of the South Lagoon were higher than in the southern regions. *R. tuberosa* propagules were first recorded in Region 5 (within which the winter survey site Noonameena is located) in January 2005 ( $0.05 \pm 0.03$  propagules/core) and only involved type II turions, which appeared at least six months prior to shoots being recorded at Noonameena.

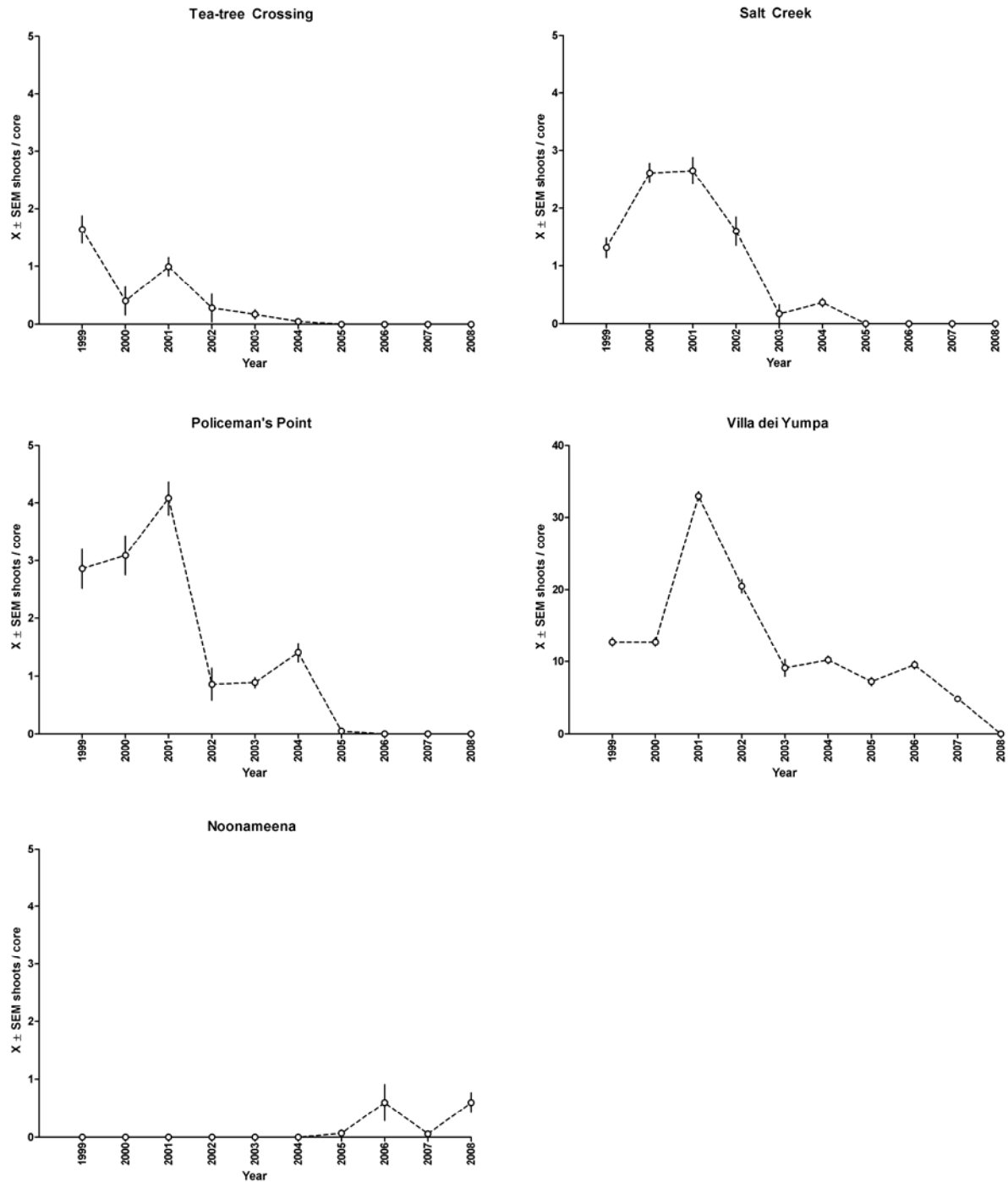
Longer-term records of propagule density provide some suggestion that the propagule banks of *R. tuberosa* in the Coorong are dynamic over longer (multi-decade) timeframes (Figure 7). While the density of propagules in each region in 1985 and 1991-2 were within the range of densities recorded between 2001 and 2008, the most recent densities recorded (particularly since 2006) all fall below any other historically recorded density. For the South Lagoon, turions accounted for 47-82% of all propagules in January for the period 2001-2006, but in 2007 turions accounted for only 15% of *R. tuberosa* propagules, and just 3% in 2008. This suggests that turions are short-lived within the propagule bank of *Ruppia tuberosa*.

### 3.1.3. Current distribution of *R. tuberosa*

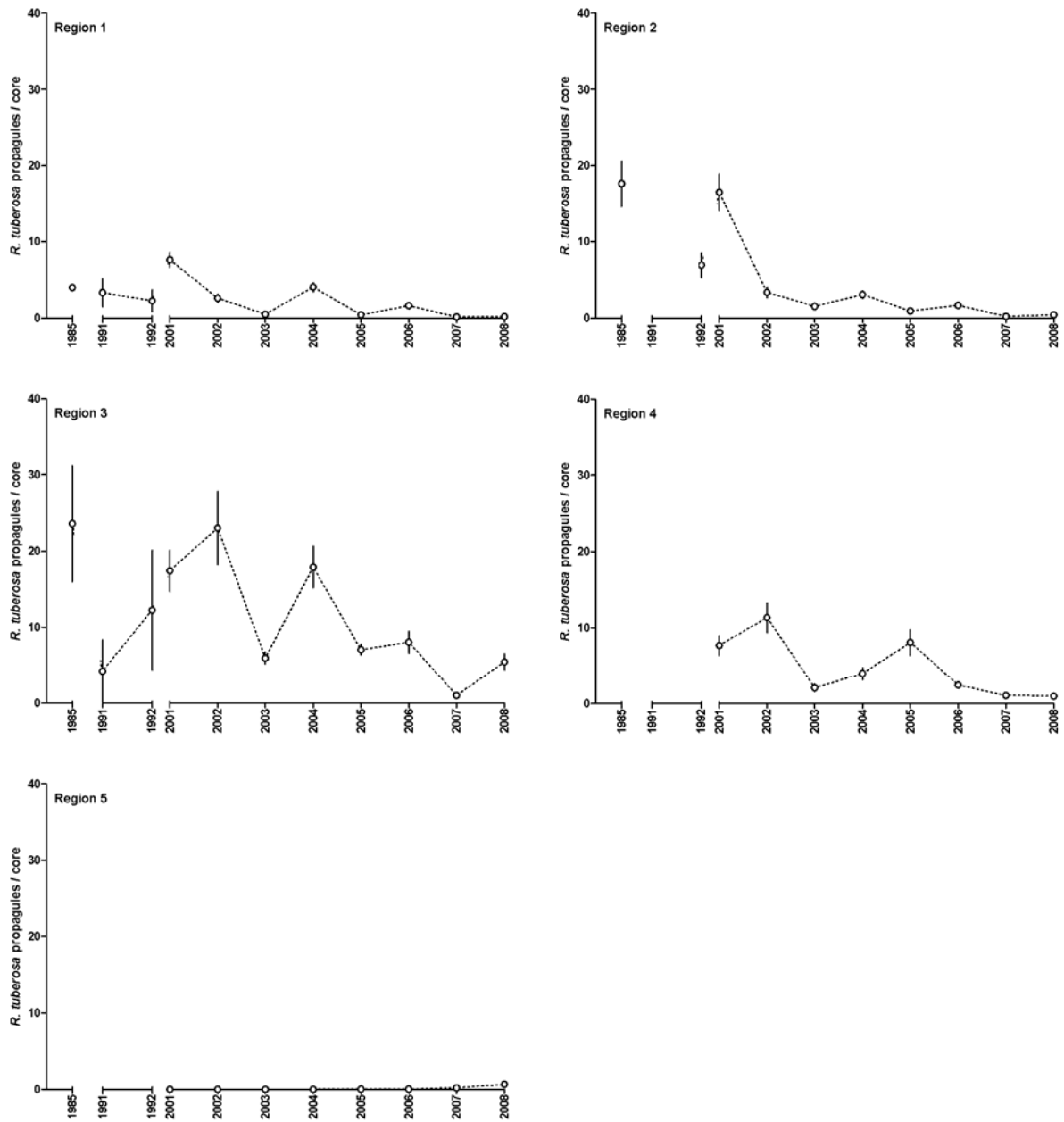
A map of the current distribution of *R. tuberosa* in the Coorong, based on the surveys described in 2.1.4, is presented in Figure 8. This survey found that *R. tuberosa* was not detected in the South Lagoon except at Parnka Point at the junction of the North and South Lagoons (Figure 8), where *R. tuberosa* shoots were recorded in one core only (estimated cover = 2%, n = 50 cores). No shoots were recorded at Magrath Flat (immediately north of Parnka Point), suggesting that *R. tuberosa* is now rare in the southernmost parts of the North Lagoon.



**Figure 5. Changes in the percent cover of *R. tuberosa* through time, at 5 sites in the Coorong. Cover was measured as the percentage of cores in which *R. tuberosa* shoots were detected, with 200 cores collected per site per year. The locations of these sites are presented in Figure 2.**



**Figure 6.** Changes in the mean ( $\pm$  SEM) number of *R. tuberosa* shoots per core recorded through time, at 5 sites in the Coorong ( $n = 200$  cores per site per year). The locations of sites are presented in Figure 2. Note the different scale on the y-axis for Villa dei Yumpa relative to the other sites. To convert the numbers of shoots per core to shoots per  $m^2$  multiply by 226.



**Figure 7. Mean ( $\pm$ SEM) number of *R. tuberosa* propagules (seeds and turions) per core recorded annually in January, in five regions of the southern Coorong. The distribution of these regions is presented in Figure 2. The number of sampling sites in each region, and the number of cores taken in each region and year are provided in Table 1 To convert propagules per core to propagules per  $m^2$  multiply by 226.**

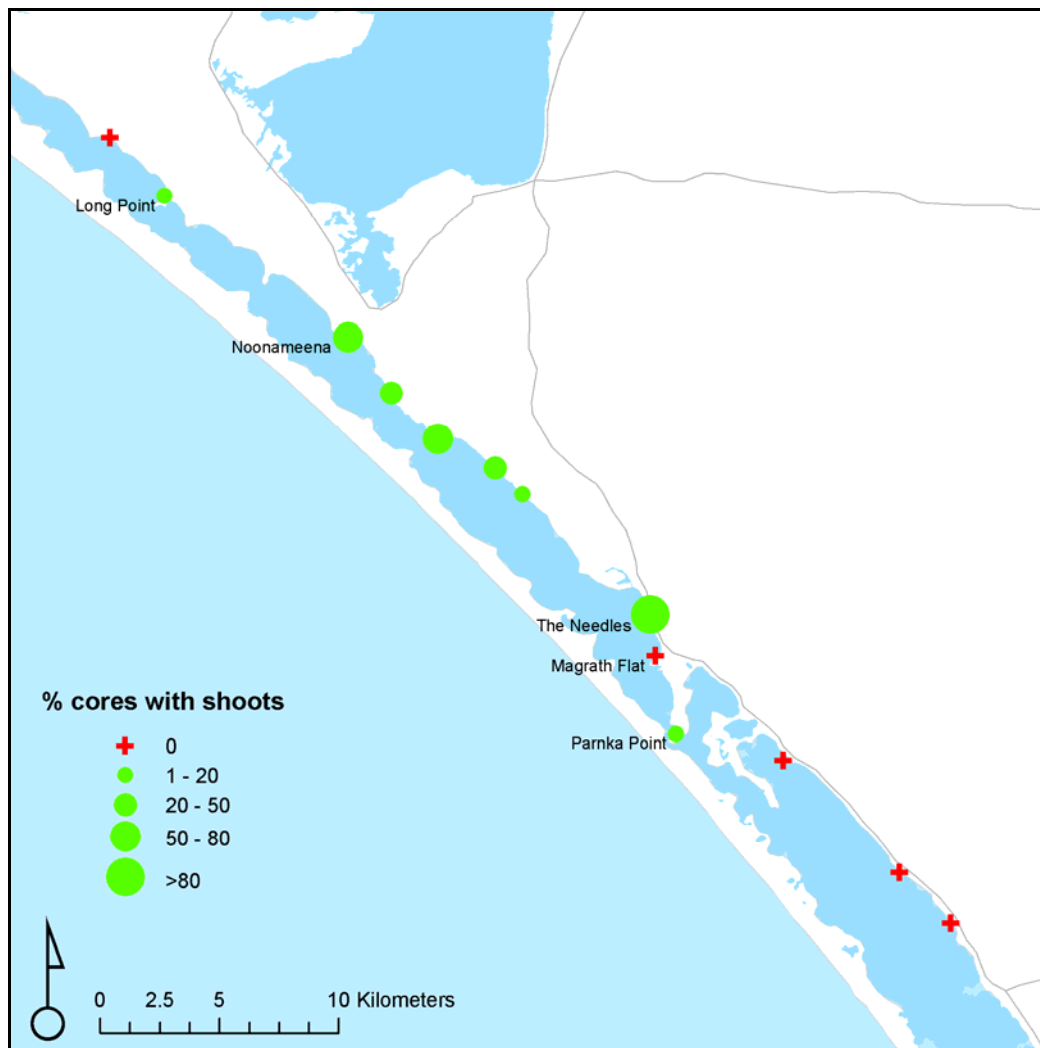


Figure 8. Map showing the current distribution of *Ruppia tuberosa* in the Coorong. 13 sites were sampled (n = 50 cores per site), focusing on *R. tuberosa*'s recent historic range.

The northernmost site in which *R. tuberosa* shoots were recorded was Long Point (estimated cover = 2%, n = 50 cores), approximately 31 km north of Parnka Point. *R. tuberosa* was not detected north of Long Point.

The current stronghold for *R. tuberosa* in the Coorong thus appears to be between The Needles (~6km N of Parnka Point) and Noonameena ~21km N of Parnka Point, a linear distance along the lagoons of ~15 km. This compares to the species' estimated distribution in 2001, when it was common throughout the entire South Lagoon, and the southern 8-10km of the North Lagoon (a distance of ~ 50km) but not at Noonameena.

### 3.2. NPMR Analysis

The best model (defined by the highest  $xR^2$  value) that explained the percent cover of *R. tuberosa* contained four explanatory variables: Mean daily salinity (X SAL), Maximum average monthly salinity (MAM SAL), Minimum average monthly salinity (MIM SAL), and water level

regime (AHD.days). The  $xR^2$  value for this model was 0.637. A comparison with Monte Carlo random runs found that the model explained a significant proportion of the variation in the percent cores that contained *R. tuberosa* ( $P = 0.048$ ). The final model thus appeared to explain a significant proportion of the variation in abundance and distribution of *R. tuberosa*. However, the absolute cover values were under-predicted by the model, with the slope of the relationship between observed and predicted cover values being 0.555 (Figure 9); this slope differed significantly from the ideal slope of 1 ( $F = 86.6$ ;  $P < 0.0001$ ).

The relative contribution that each of these parameters made to the final model are described in Table 2. The tolerance of each parameter is inversely proportional to the importance of that parameter to the local model, while the sensitivity of each parameter refers to the sensitivity of the response variable to incremental changes to the value of the explanatory variable (McCune 2006). As shown in Table 2, the parameter that explained the greatest variation in the percent of cores that contained *R. tuberosa* shoots was the minimum average monthly salinity (tolerance = 13.6; sensitivity = 1.62), while the parameter that explained the least variation (among those parameters included in the model) was AHD.days (tolerance = 71.9; sensitivity = 0.043).

**Table 2. Tolerance and sensitivity values calculated for the four explanatory variables that were included in the best model. Tolerance is inversely proportional to the importance of an explanatory variable to the model, while sensitivity is directly proportional to the importance of an explanatory variable. The  $xR^2$  value for the best model was 0.637.**

Variable	Tolerance	Sensitivity
X SAL	43.4	0.185
MAM SAL	54.3	0.2
MIM SAL	13.6	1.62
AHD.DAYS	71.9	0.043

Figure 10 to Figure 13 show the predicted responses of *R. tuberosa* (expressed as predicted % cores that contain shoots) to each of the hydrological explanatory variables in the final model. *Ruppia tuberosa* responded similarly to all salinity variables. *Ruppia tuberosa* cover varied with salinity along a bell-shaped curve, with the highest predicted cover found at salinities of between  $72\text{gL}^{-1}$  (for minimum average monthly salinity from May to November; Figure 10) and  $98\text{gL}^{-1}$  (for maximum average monthly salinity from May to November; Figure 11). These bell-shaped responses to salinity coincide with the predicted functional responses, where upper salinity limits are physiologically-based, while lower salinity limits are likely to be based on the upper physiological salinity tolerance of an important epiphytic algae, *Enteromorpha* spp. (see Discussion, and section below).

The response of *R. tuberosa* cover to water level (as defined by the parameter AHD.days) suggests that low water levels are more significant in limiting *R. tuberosa* than high water levels (Figure 13). A curvilinear increase in *R. tuberosa* cover was observed up to ~100 AHD.days, at which point an increase in water level regime had no effect on *R. tuberosa* cover.

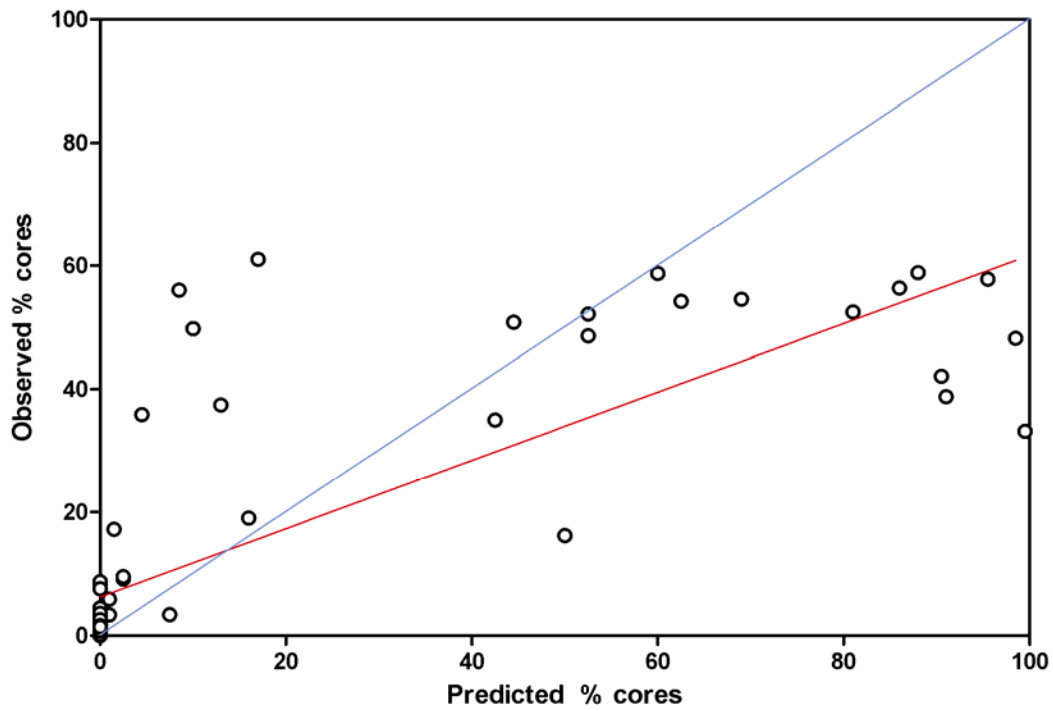


Figure 9. Predicted versus observed *R. tuberosa* cover (expressed as the percent of cores containing shoots) for the best NPMR model for PCORES ( $xR^2 = 0.637$ ). The blue dashed line represents the 1:1 slope, while the red solid line represents the slope of the straight line through the data points (Slope = 0.555, Spearman R = 0.832). For a perfect fit model, the observed slope should equal the 1:1 slope.

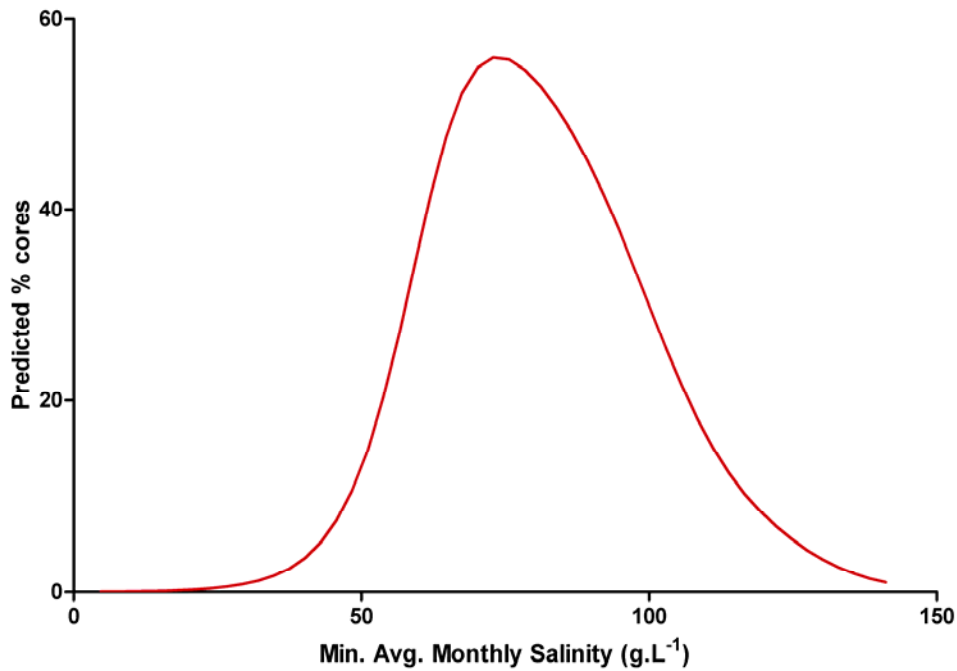


Figure 10. Predicted response curve of *R. tuberosa* (response expressed as the percent of cores that contain shoots) to minimum average monthly salinity (parts per thousand, TDS). Predictions were drawn from the final NPMR model ( $xR^2 = 0.637$ ; see text).

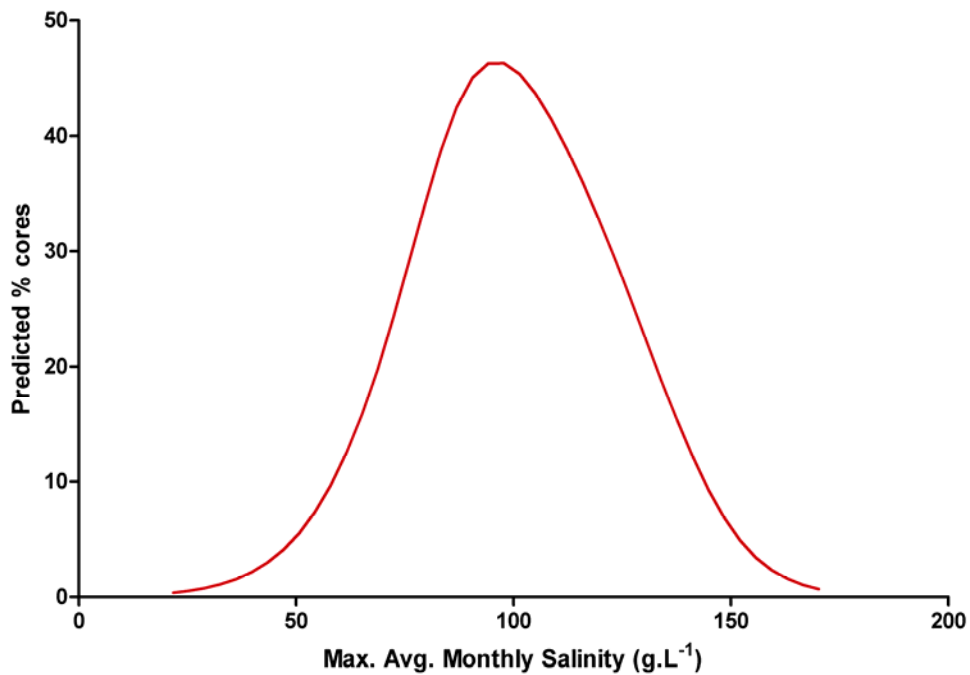


Figure 11. Predicted response curve of *R. tuberosa* (response expressed as the percent of cores that contain shoots) to maximum average monthly salinity (parts per thousand, TDS). Predictions were drawn from the final NPMR model ( $xR^2 = 0.637$ ; see text).

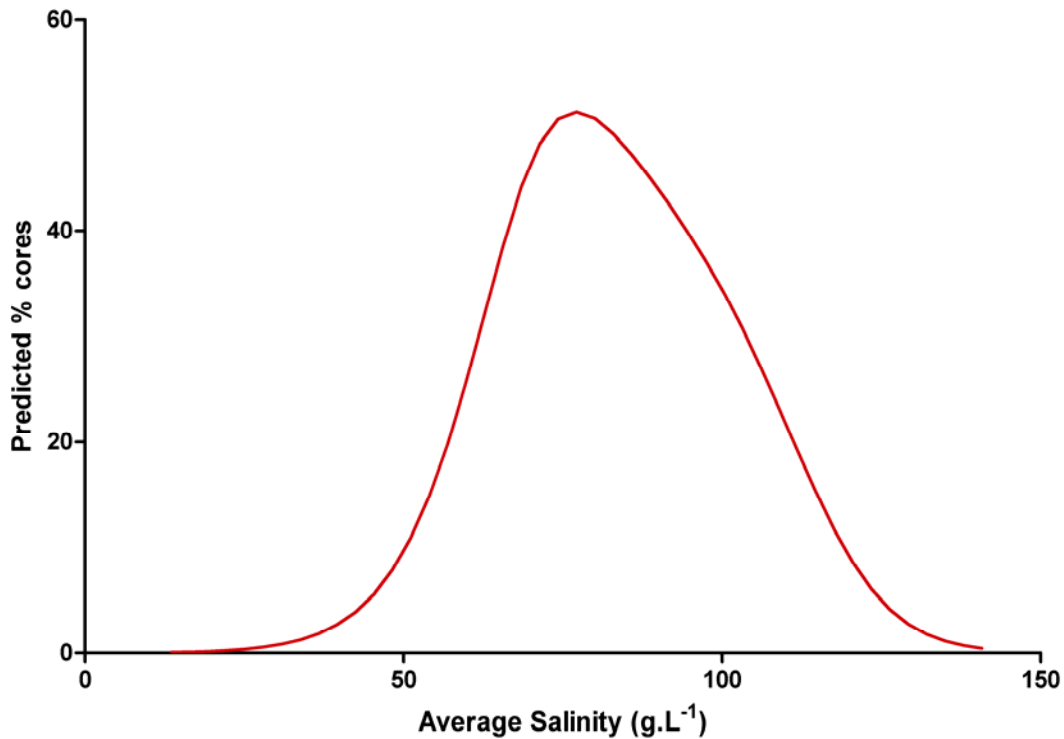


Figure 12. Predicted response curve of *R. tuberosa* (response expressed as the percent of cores that contain shoots) to average daily salinity (parts per thousand, TDS). Predictions were drawn from the final NPMR model ( $xR^2 = 0.637$ ; see text).

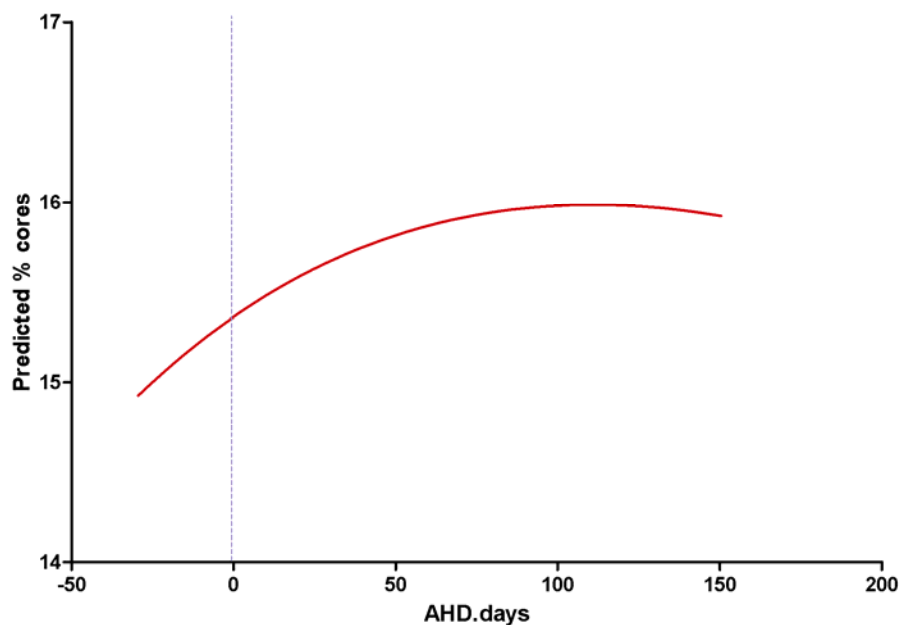


Figure 13. Predicted response curve of *R. tuberosa* (response expressed as the percent of cores that contain shoots) to water level regime (AHD.days, m.days). Predictions were drawn from the final NPMR model ( $xR^2 = 0.637$ ; see text). Note the difference in the scale compared to Figures 10-12)

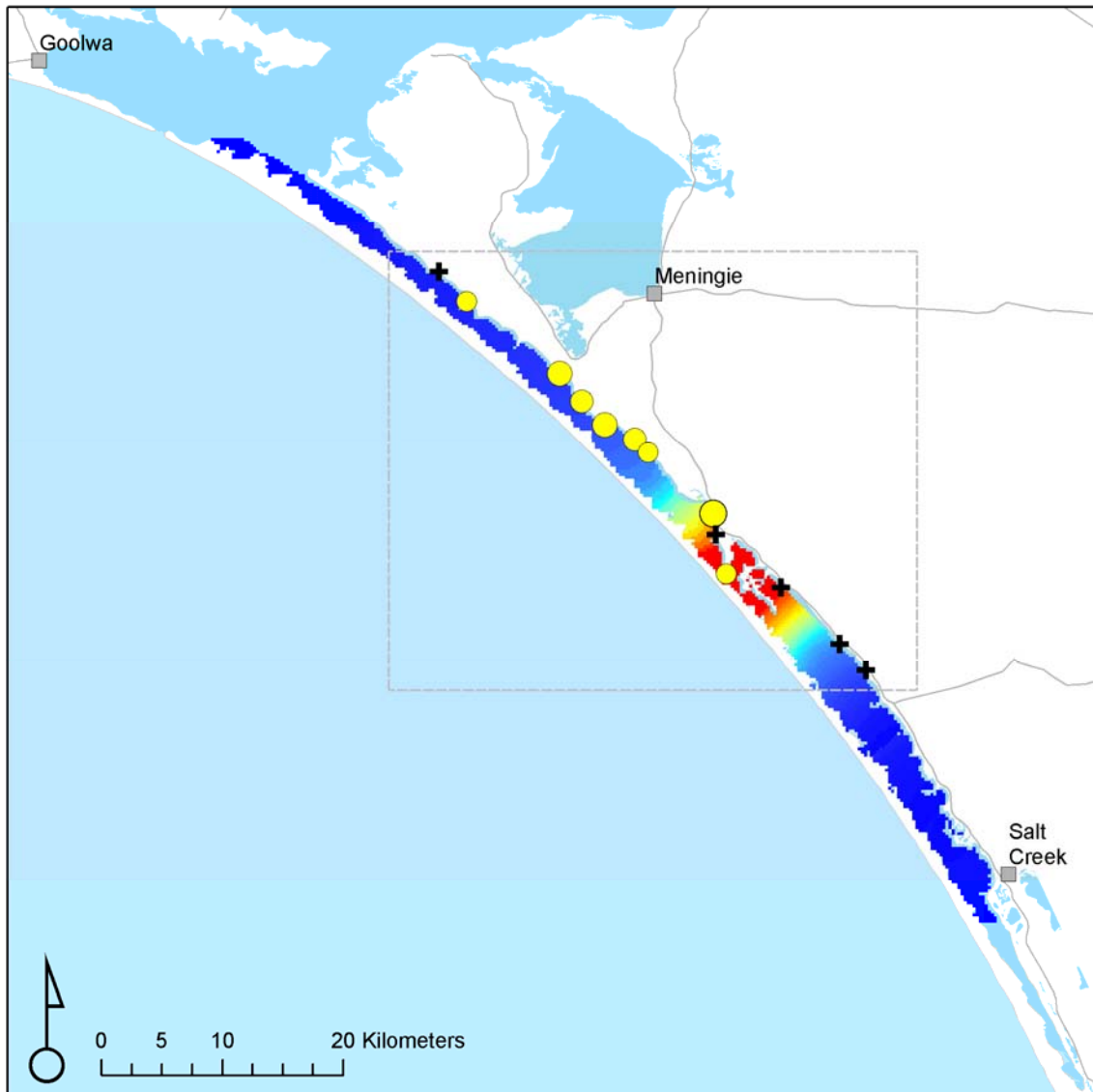


Figure 14. Map of the Coorong, showing the predicted and actual distribution of *R. tuberosa* (actual distribution taken from the current distribution survey described in Section 3.1.3). The predicted values for *R. tuberosa* percent cover range in colour from dark blue (low percent cover) to red (high percent cover): the model thus predicts that high cover *R. tuberosa* is currently restricted to the southern parts of the North Lagoon and the northern parts of the South Lagoon. The yellow points here are the current values for percent cover (from Figure 8), with the range of the current distribution survey given by the hashed box.

## 4. Discussion

### 4.1. Changes in distribution and abundance

The key finding from this study is that, in the space of ten years, *Ruppia tuberosa* has largely disappeared from the South Lagoon of the Coorong. In 1999, the percent of cores that contained *R. tuberosa* shoots ranged from 33% to 91% among the four South Lagoon sites. In 2005, *R. tuberosa* was not detected at the two southernmost of these sites, in 2006 it was not detected at one further site, and in 2008 it was not detected at any of the four sites. This dramatic decline in distribution and abundance (supported by similar patterns for shoot density) was also associated with limited expansion into the North Lagoon of the Coorong, with *R. tuberosa* recorded at Noonameena for the first time in 2005.

Spatiotemporal changes in the abundance of propagules largely mimicked the changes observed in shoot distribution and abundance, although the rates of decline in the South Lagoon were less pronounced for propagules than for shoots. A small propagule bank consisting of seeds still persists in the South Lagoon (regions 1-3 in Figure 7), but many of these seeds may be buried too deep in the sediment to enable germination. The viability of the seeds in these propagule banks is also very low, with perhaps no more than 1% being viable (Paton & Rogers unpubl.). Kantrud (1991) recorded *in situ* survival times of up to three years for annual species of *Ruppia*, although quantitative data are generally poor regarding the persistence of both seeds and turions in the propagule bank. Understanding the propagule bank dynamics of *R. tuberosa* is critical for its future management, given that the plant has failed to reproduce for more than three years across the South Lagoon, even in areas where germination has taken place. If propagule banks have limited capacity to survive during periods of adversity then populations are unlikely to persist when faced with on-going conditions where the plant fails to reproduce. Re-establishing populations of *Ruppia tuberosa* in the South Lagoon may now be difficult without additional intervention (translocation of plant material) given that few if any viable propagules remain. Natural re-colonisation is also likely to be slow based on the time *Ruppia tuberosa* is taking to become prominent after initial establishment in 2005 at Noonameena midway along the North Lagoon.

The recorded decline of *R. tuberosa* in the Coorong South Lagoon has important ramifications for other components of the ecosystem. Smallmouth Hardyhead (*Atherinosoma microstoma*) have also shown significant declines in recent history (Paton 2005; Paton *et al.* 2009b; Rogers and Paton 2009, although this decline may be related to the direct physiological impact of salinity on this species (Lui 1969), in addition to its dependence on *Ruppia* to provide habitat. More direct evidence comes from the significant declines observed for some waterfowl species, particularly Black Swan (*Cygnus atratus*; Rogers and Paton 2009), that depend almost exclusively on submerged aquatic vegetation as a food resource (Marchant and Higgins 1990). The relationships between spatiotemporal changes in food supply and bird abundance are discussed in more detail in Rogers and Paton (2009).

## 4.2. Model Predictions

The final NPMR model suggested that a combination of four hydrological (three salinity, one water level regime) variables provided the best prediction for spatiotemporal changes in *R. tuberosa* cover. This model had a reasonably high  $xR^2$  value of 0.637, although the model under-predicted the absolute values for *R. tuberosa* cover (slope of line for observed vs predicted values = 0.555).

The NPMR analysis suggested that the observed spatiotemporal changes are related primarily to changes in the Coorong's salinity regime. Of the four explanatory variables included in the final model, three related to salinity; furthermore, the only water level parameter (AHD.DAYS) explained the least amount of variation in *R. tuberosa* cover of the four included variables (as determined by sensitivity and tolerance indices).

When the predictions of the model for 2008 were compared with the actual distribution of *R. tuberosa* (as recorded by the current distribution survey described in Section 3.1.3), two observations can be made. First, the model appeared to successfully predict the severe northward contraction of *R. tuberosa* for the South Lagoon of the Coorong with the species predicted to be absent from all but the northernmost 5-10km of the South Lagoon. Nevertheless the model predicted that the decline would not be as severe as field surveys suggested, with the model predicting that *R. tuberosa* should be abundant in the top 5-10 km of the South Lagoon, yet none was found. Second, the model failed to predict the extent of the northward expansion of *R. tuberosa* into the North Lagoon of the Coorong. The current distribution survey found *R. tuberosa* shoots up to 31 km north of Parnka Point. Although the model predicted that this site and most of the North Lagoon would have relatively low values for cover, except the southernmost 5km, significant quantities of *Ruppia tuberosa* were detected further north of this 5km section from 10-20km from Parnka Point.

One of the primary reasons for this disparity may be the non-causative nature of the model, coupled with the limited data on which the model is based. The first of these issues may be overcome through the development of a functional response model for *R. tuberosa* that accounts for the direct and indirect functional relationships between the Coorong's hydrology and the population demography of *R. tuberosa*, particularly the production, dispersal and survival of propagules. Such a model requires a good quantitative understanding of these relationships, which is currently lacking. The current correlative model predicts that *R. tuberosa* responds within a range of salinities between about 30 and 160gL<sup>-1</sup> (Figures 10-12) yet the plant has been recorded in higher and lower salinities than these (Nicol 2005). Furthermore the models have been based on data collected during a population crash and this may account for the model's inability to predict expansions in distribution. More research is therefore required, in order to develop a functional response model to provide the predictive power required. The second issue raised, relating to limited datasets, can be overcome by committing to long-term monitoring programs for key species such as *R. tuberosa*. Through the future collection of response data, existing models (such as the one presented in this report) can be continually updated and modified, with subsequent improvements in the ability of the models to predict responses to hydrological change.

## 5. Summary, Conclusions and Management Implications

*Ruppia tuberosa* has historically been an integral component of the Coorong's South Lagoon ecosystem, providing a food resource and habitat for key bird and fish species. However, annual monitoring of shoots and reproductive propagules since 1999 has shown that *R.*

*tuberosa* has declined significantly in distribution and abundance. The northward shift in the distribution of *R. tuberosa* is evidenced by two observations: *R. tuberosa* has declined sequentially along the South Lagoon from south to north, while expansions into the central sections of the North Lagoon have only been recorded since 2005. This evidence suggests that conditions that were suitable for *R. tuberosa* in the South Lagoon are now only found in the southern and central parts of the North Lagoon.

Non-parametric multiplicative regression (NPMP) found that the hydrological variable that best explained this spatiotemporal change was the minimum average monthly salinity during May to November, with two other salinity variables and one water level variable also included in the best model. While the spatiotemporal variation in *R. tuberosa* cover that was explained by this model was high, it failed to predict with accuracy either the absolute levels of cover, or, significantly the northward expansion of *R. tuberosa* into the central reaches of the North Lagoon. Further development of this model is required to improve its predictive power.

With model improvements, the results presented here can be used by management agencies to predict the distribution of *R. tuberosa* in the Coorong, in response to future environmental change or alternative management scenarios. Future scenarios may lead to alternative hydrological regimes in the Coorong that will have implications for the distribution of *R. tuberosa*. Predictions from models, even the current model, will allow managers to make decisions that are better informed. In addition, management scenarios can be designed to optimise the distribution of *R. tuberosa* in the Coorong, while taking into account the hydrological requirements of other key biota.

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